A DECISION SUPPORT SYSTEM FOR GROUND IMPROVEMENT METHOD SELECTION

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ABSTRACT

Ground improvement has become such a common construction practice that the foundation for any important structure that is constructed today is likely to have met some form of ground improvement technology. The improvement option is usually adopted whenever poor quality soils underlie the site proposed for the location of a new facility or for remedial works on existing structures.

Numerous improvement techniques are known. When faced with the problem to find an appropriate ground improvement methodology, decision-makers often have to consider a wide variety of factors. The selection of the most suitable method for the solution of the problem has itself become a problem based on the number of factors to consider, the numerous uncertainties associated with the ground conditions and the possibility that for a particular problematic ground condition, more than one method can be used to solve the problem. In order that the ground improvement consultant conducts his or her work with a high level of confidence it is thought that an independent view from a reliable assistant may be worth while.

A prototype decision support tool, **GrIMSA**, (**Gr**ound **I**mprovement **M**ethod **S**election **A**ssistant) has been developed to assist the geotechnical engineer during the preliminary stages when considering the use of ground improvement technology. The tool implements a rational systematic technique for selecting the most appropriate and cost-effective ground improvement method for a construction site. The technique is based on a consensus of standards in the ground improvement domain and is designed to be practical, flexible and transparent. The sources of knowledge upon which the system is based is mainly from practicing ground improvement domain experts in various parts of the world and published technical literature on ground improvement projects.

GrIMSA suggests a limited number of appropriate ground improvement methods from 32 possible methods that could be used in solving the foundation problem. The final decision on the method to use however is left for the user to make by applying his or her personal engineering judgement based on site specific conditions.

GrIMSA is aimed at experienced geotechnical engineering consultants and contractors. The system has been developed using the wxCLIPS software.

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CHAPTER 1

INTRODUCTION

1.1 General Introduction

Ground improvement technology has been resorted to as a construction technique on soils with inadequate properties with the view to increase the soil shear strength, reduce soil compressibility and also to reduce soil permeability. The practice dates back several centuries. However, there has been a greater awareness in the use of ground improvement technology in the last three or so decades with new methods being developed based often on local experience, in many parts of the world. Some of the techniques are highly specialized and consequently, are used by only specialist contractors.

As soils with inadequate properties can be found on any construction site in the world, it has been found appropriate to transfer ground improvement know-how worldwide among geotechnical engineers as a means of forging worldwide technology transfer through an appropriate process. Because ground improvement is a specialized area in geotechnical engineering, the information regarding this area is generally limited to specialist contractors and consultants. Technology transfer is not very wide in the ground improvement domain as many of the methods are patented and can be used by only a few consultants/contractors. Consequently, many geotechnical engineering consultants or experts have limited knowledge about some of the numerous techniques that are in operation and may never recommend the use of such methods that he/she has very limited knowledge about even though these methods may be the most appropriate for the job.

The scope of this research is to present a methodology that allows the use of knowledge-based system technology to develop a decision support system that would assist the ground improvement expert in the selection of an appropriate method of ground improvement when the need arises. The approach does not limit the engineer/consultant to the methods already known to him, but includes many ground improvement methods that are used world-wide.

Since ground improvement is a relatively secluded area in the geotechnical engineering field, an extensive review of the literature was conducted for knowledge on the numerous ground improvement technologies that have regularly been used for the solution of many poor soil foundation problems and the new or innovative methods, which though suitable, have still not yet gained wide recognition or acceptance by the ground improvement community. This knowledge was further augmented with knowledge obtained by talking to and sourcing knowledge from people who are experienced in the ground improvement domain area.

The information gathered form these sources have been used in the design of a decision support system for ground improvement method selection. The system includes explicitly recorded knowledge statements or facts on ground improvement methods. The decision support system is constructed to ensure that in the event of the need to use ground improvement technology at a construction site, decisions on the choice of method can be made based upon the consideration of the relevant information pertaining to ground improvement methods in use now and proposed. The system suggests a number of appropriate methods that could be used to improve the properties of the underlying problematic soil(s) in order to make the site suitable for the location of a new facility. It could also be used when there is the need to improve the foundation soils of existing structures.

To achieve this, the approach adopted comprised acquiring knowledge in the ground improvement domain area and storing the acquired knowledge and making the knowledge useable by means of a computer program **GrIMSA (Ground Improvement** Method Selection Assistant).

When considering the use of ground improvement methodology, **GrIMSA** can be used to provide various levels of support to the geotechnical engineer or ground improvement expert to suit different needs in knowledge analyses such as the identification of the types of problematic soils underlying a project site, assessment of the need for ground improvement or making a decision on one or a composite of improvement methods from the numerous ground improvement techniques that are known.

1.2 Organization of the Thesis

This thesis is organized as follows:

An overview of some of the common ground/soil improvement techniques is presented in Chapter 2. The chapter starts with a brief review of the occurrence of the most common problematic soils in the construction industry citing some of their engineering properties where applicable. This is followed by a review of the types of engineering facilities that are developed on problematic soils. The basic concepts of some of the frequently used ground improvement techniques are also discussed.

In Chapter 3, the various types of civil engineering facilities that have been or can be developed on problematic soils are discussed. This is immediately followed by the type of problems that are encountered when these structures are placed on problematic soils. In order to properly understand the problem and thereby make appropriate decisions on the type of method to use a discussion on the choice of soil parameters to consider for a site investigation program is presented followed by a discussion on the construction options that could be used.

Since one of the objectives of the thesis is to describe the development of a decision support system for ground improvement, a literature review of the application of knowledge-based systems technology in the geotechnical engineering domain is presented in Chapter 4. An attempt is made to cover all the areas of geotechnical engineering that the subject of knowledge-based systems technology has touched. This is done with the view to demonstrate the fact that though few prototype knowledge-based systems or expert systems are known for ground improvement, the technology is feasible in the ground improvement domain, as it has been applied in other fields of geotechnical engineering.

In Chapter 5, a brief discussion of the aims and objectives of the system development in addition to the considerations affecting the selection of the development tool are presented. Details of the sources of knowledge for the development of the decision support system including the methods adopted for the knowledge abstraction and analyzing the knowledge gathered are described. The various characteristics that are used for the identification of the problematic soils presented in this thesis are also discussed. In addition, the factors that are normally considered in the selection of a ground improvement methodology are presented.

In Chapter 6, the compilation of the knowledge-based system is presented. The chapter starts with a brief description of the CLIPS development environment. The construction of the knowledge bases that were found suitable to handle the data collected on ground improvement is discussed. This is followed by a discussion of the use of certainty factors to describe the confidence with which each method suggested has been selected.

The evaluation of the prototype decision support system is presented in Chapter 7. The evaluation process is carried out in two stages namely verification and validation. The verification stage involved checking and verifying the syntax of the system. Validation of the system was conducted through the assessment of seven case studies. The case studies were taken from known ground improvement projects in various parts of the world.

The conclusions drawn from the development of the methodology and the prototype decision support system in this thesis are presented in Chapter 8.

Future developments to enhance the performance of the system are discussed in Chapter 9.

CHAPTER 2

GROUND IMPROVEMENT TECHNOLOGY - AN OVERVIEW

2.1 Introduction

The term ground improvement embraces all those special construction techniques that are conducted on a ground environment which upon testing has proved to possess properties that are unsuitable for the development of new or proposed structures or continue to support existing structures on it with the intension of improving the quality of the soils or rock. The term has been used broadly to incorporate all methods of treatment of soil or rock in-situ or otherwise with the view to altering the properties of these materials in order to meet specification requirements of the proposed facility or structure.

Ground improvement is mainly carried out on problematic soils. These are soils with marginal properties thus making them incapable of supporting structures developed on them. Many types of poor soil materials exist. Prominent among them are soils which are classified as collapsible soil, expansive soil, soft clay, liquefiable soil, sensitive clays, compressible and organic soils. Many of these soils are susceptible to loss of strength and stiffness; have high compressibility, etc, which may result in bearing capacity failure, liquefaction, settlement, etc. Consequently, facilities such as roads, bridges, dams, houses and many others constructed on these soils are subjected to significant damage with the potential for very large economic losses. Present demand for land use particularly in urban and suburban areas, population increase and a host of factors have necessitated the use of grounds underlain by the above soil types and which hitherto would never have been considered suitable for the location of a civil engineering facility. To achieve design standards therefore, ground improvement technology has found a place in the civil or geotechnical field.

The concept of ground or soil improvement is not particularly new. Several soil improvement techniques (non-documented though) have been used for several thousands of years as a means of improving the geotechnical engineering properties of soils for one purpose or the other. Each community has practised one or several improvement methods, which though may not be globally recognized has had great impact on the social advancement of that community. The background to the use of these methods may have been on intuition rather than theoretical. Holtz (1991) has cited a number of reinforced soil legendaries such as The Great Wall of China (200BC) as an attestation to this fact. The use of timber piles bedded in sand to form a timber raft over compacted clay in Norway in the 12th century is documented by Flodin & Broms (1981).

In modern day times, various techniques have been used for the improvement of soils and ground for the location of important structures or facilities such as nuclear power stations, bridges, industrial structures, residential structures, tunnels, schools and many more. In the widest sense, the improvement includes compaction, total or partial replacement of the poor soil, or the use of added materials such as lime, rice husks, natural fibre and cement. Many new techniques are still evolving. Lamentable however, is the fact that many of the methodologies lack any theoretical basis albeit been effective in their applications. A majority of these techniques evolved when there was a crisis. For instance, Kimura et al. (2000) have reported the use of solidified coal ash in place of sand compaction piles for the improvement of soft ground in both marine and terrestrial environments in Japan when the demand for cement started dropping in the mid-90s. (Coal ash is a raw material for cement production and as a consequence of the drop in demand for cement an alternative use of large stock piles of coal ash, from thermal power plants, had to be found). Field trials are often then resorted to for verification of the idea. Even though there are no generally accepted theoretical design procedures, successes in the developed techniques have now led to the successful construction of numerous structures such as mentioned above on problematic soils, which hitherto would not have been attempted.

Descriptions of improvement techniques to decrease permeability or to increase the strength and decrease compressibility of soil formations and rock masses abound in the literature. The application of these techniques, however, varies due to a number of factors including:

- Soil type
- Rock mass condition
- Desired depth of improvement and
- Proposed construction

which must be considered during the early site planning stages. Some of the techniques are applicable to post construction corrective measures (Hunt, 1986).

This chapter gives an overview of some of the common ground/soil improvement techniques that have been used over the years in solving numerous foundation problems on/in problematic soils. The chapter begins with a brief discussion on the occurrence of problematic soils in Section 2.2. This is followed by a brief description of the engineering properties of the various problematic soils such as weak and compressible soils with emphasis on soft clays, collapsible soil (e.g. loess), expansive clays and corrosive soils in Section 2.3.

The applications of ground improvement are presented in Section 2.4. Section 2.5 discusses some of the ground improvement techniques that are commonly used by the specialist ground improvement contractors. The discussion is broadly on the basic concepts of the methods with the aim of showing the applicability of each method but with little or no coverage on equipment. No attempt has been made to cover detailed design methods due to lack of space and time. The advantages of using some of the methods where applicable are indicated.

Some questions that may arise during the design stage are cited in Section 2.6. A brief discussion on the various types of ground improvement techniques is presented in Section 2.7. The conclusions to the chapter are drawn in Section 2.8.

2.2 Occurrence of Problematic Soils

Problematic soils have wide geographic distribution covering all the continents of the globe. The occurrence of soft clays is well documented to the Scandinavian countries in particular, Canada, the northern parts of the United States, Mexico, Thailand and the deltaic regions of the world's major rivers (Flodin & Broms, 1981), where the deposits may be more than 100m in thickness. Clayey expansive soils termed black cotton soils are reported to cover over 30% of India (Sorochan, 1991). They are also found in countries such as Egypt, South Africa, Burma, Sudan, the former USSR and other countries. These soils become particularly problematic in arid, semi-arid and predominantly wet climatic areas.

The clays have varied origins ranging from glacial to post glacial, marine, volcanic, igneous and alluvial. Marine clays are the most predominant forms of soft clays. It is believed that the terrestrial soft clay deposits are among the youngest sediments on the

Geologic Time Frame (Brenner et al., 1981) and as such have undergone little diagenetic changes due to isostatic uplift after the glacial era and marine regression.

Soft clays and expansive clays are by far not the only known soil types that pose a lot of construction problems to the geotechnical engineer either during the construction stage or after the development of the structure and therefore lend themselves to improvement. The suites of soils that classify as problematic include:

- Weak and compressible soils (soft clays, highly organic soils).
- Expansive soils (smectite clays).
- Collapsible soils (usually of alluvial or aeolian origin with high void ratio, low moisture content and a honey-comb or highly porous structure maintained by water soluble interparticle bonds).
- Frozen soils.
- Corrosive soils.
- Liquefiable soils.

Geologically, collapsible soils mostly occur in arid regions. Large areas of land around the world are reported to be underlain by collapsible soils. For instance Liu et al. (1964), Liu (1985) have indicated that about 6.6% of the total area of China is underlain by loess – a type of collapsible soil. Collapsible soils are usually aeolian or alluvial in origin and posses a honeycomb structure or highly porous structure that is maintained by water-soluble interparticle bonds. Collapsible soil can compress due to a break down of these bonds following the ingress of water (Coduto, 1999). According to Sabatini et al. (2002) three types of collapsible soil are known namely: (1) loose man-made fills (2) colluvium and (3) loess. These soils usually exist in the ground at relatively low values of dry unit weight and moisture content.

Frozen soils are found in regions with cold climates where there is seasonal soil freezing as well as in the high latitude permafrost regions (Carter & Bentley, 1991; Coduto, 1999). In these regions, freezing of the soil occurs when the air temperature falls below 0° for extended periods resulting in drops in the soil temperature to a comparable level and subsequently turning the pore water into ice.

Corrosive soils develop in regions where there is fluctuating elevation of groundwater such as tidal zones where the process introduces both water and oxygen, and also in contaminated soils such as sanitary landfills and shorelines in the proximity of old sewer outfalls. Corrosion is a nearly universal concern with steel and iron (Coduto, 1999). The majority of soils however are non corrosive to cast iron.

The Dictionary of Soil Mechanics and Foundation Engineering defines liquefaction as "*the state existing when saturated sandy soil loses shearing strength and effective stresses are reduced as a result of increased pore water pressure*". Liquefaction phenomenon occurs in areas where the ground is composed of saturated loose sandy soil. When such ground is subjected to stresses due to repeated earthquake motion, the pore water pressure rises in the soil and the effective stresses in the soil are lost resulting in the eventual lost of the strength of the ground (The Japanese Geotechnical Society, 1998). Liquefaction is a common phenomenon in earthquake prone zones of the earth such as Eastern Asia (in particular Japan) and the west coast of the United States.

Numerous types of problems (to be discussed later in Chapter 3) are associated with these soil types prominent among which are:

a) Settlement problems
b) Bearing capacity
c) Stability

Flodin & Broms (1981) describe briefly the characteristics of some of these deposits and also a number of landslide episodes associated with soft clays. The spectacular failures presented by soft clays in Sweden and Norway in particular and Canada has led to the development of techniques for the improvement of their engineering characteristics.

2.3 The Engineering Characteristics of Some Problematic Soils

2.3.1 Soft Clays

The basic engineering properties of soft clays are their consistency and physico-chemical properties, strength, compressibility and settlement. These soils are characterized by possessing low strength, high deformability and low permeability.

They pose stability problems and normally undergo high settlements. The geotechnical characteristics of some of the known soft clays across the globe are shown in Table 2.1.

Property	Identification					
	Bothken-nar	Cuenco de Mexico	Ariake	Singapore soft clays	Bangkok clays	Indian marine clays
	Scotland	Mexico	Japan	Singapore	Thailand	India
	Nash et al. (1992)	Diaz-Rodrignez et al (1998)	Tanaka et al. (2001)			Rajasekaran et al. (1999)
Major clay mineral	-	smectite	smectite	kaolinite	smectite	-
w_n (%)	30-65	220-420	90-150	50-60	55-60	36-74
w_l (%)	65-80	338	65-130	65-80	45-85	41-82
I_p (%)	25-55	308	40-100	40-60	30-70	
Activity	1.34	-	1.0-2.0	0.5-0.8	0.9-1.4	2.14-2.61
Clay (%)	20-36	2.4-12	50	65	50	16-72
e_o	1.02-1.98	-	-	-	-	-
OCR	1.4-1.6	-	1.2-1.7	1.1-1.4	1.3-1.7	-
s_u (kPa)	20-60	-	-	-	-	-
Sensitivity	5-13	-	-	-	-	-
OMC (%)	3-8	0-10.6	-	-	-	1.0-5.1
M_v cm^2/kg	-	0.1	-	-	-	-
C_v cm^2/day	-	-	100	30	10	-
C_c	-	-	-	-	-	0.37-0.81

Table 2.1: Geotechnical Characteristics of Some Soft Clays.

Notes: w_n = field moisture content   su = undrained shear strength wl = Liquid limit

C_v = coefficient of consolidation   OCR = Over consolidation ratio I_p = Plasticity Index

M_v = Modulus of volume change   OMC = organic matter content e_o = initial void ratio

C_c = Compression index

In general the clays have very high natural moisture contents - values that are either close to or far in excess of the liquid limits of the soils. The high moisture contents apparently, explain the low strength values of these clays. Smectite appears to be the dominant clay mineral among the examples shown however, its influence on the clay properties is not very well marked. For instance when comparing the Cuenco de Mexico clay, the Ariake and Bangkok clays, the Cuenco de Mexico clay has much higher moisture content, liquid limit and plasticity index even though it has a lower clay fraction range of 2.4 – 12 % in comparison with the 50% clay fraction of these two other soft clays. There is no uniqueness in the values as seen in the table even though the above generalizations are correct. Most soft clays are regarded as normally consolidated however, Parry and Wroth (1981) indicate alluvial clays usually in a real sense exhibit the characteristics of lightly over consolidated clays as a result of changes in static groundwater level and secondary or delayed consolidation.

2.3.2 Peat/Organic Soils

Peat is generally described as a mixture of fragmented organic material derived from vegetation which has been chemically changed and fossilized (Edil, 1983). According to Jarret (ed) (1982) the Organic Sediments Research Centre (OSRC) – University of South Carolina defines peat as material which has 25% ash or less inorganic material on a dry weight basis. Peat occurs extensively in many parts of the world. It is generally considered to be one of the worst of foundation materials due mainly to its high water content and compressibility and low bearing capacity.

Landva, et al. (1983) have indicated there are two major classification systems of peat used by engineers namely the von Post system and the Radforth system of classification. The von Post system of classification which is mainly based on horticultural, agricultural and forestry requirement is not considered for the purpose of this study. The Radforth system (Table 2.2), which is mostly used by engineers classifies peats and organic soils into four groups based on their engineering properties as Peats (Pt), Peaty Organic soils (PtO), Organic soils (O), and Silts and Clays with organic content (MO and CO respectively).

Classification	Property						
	A_c (%)	G_s	w_n (%)	γ_d (kN/m^3)	Fibre content (%)	H_x likely to be	I_p (%)
Pt	<20	<1.7	>500	<2.7	>50	H_{1-8}	-
PtO	20-40	1.6 - 1.9	150 - 800	1.7 - 3.0	<50	H_{8-10}	-
O	40 - 95	>1.7	100 - 500	-	insignificant	H_{10}	> 50 (OH)
MO, CO	95 - 99	>2.4	<100	-	-	-	<50 (OL)

Table 2.2: The Radforth System of Classification of Peats and Organic Soils (adopted from Landva, et al., 1983)

Notes: H_x = degree of humidification on a scale of x = 1 to 10.
(H_1 = living plant, H_{10} = completely decomposed) γ_d = dry unit weight G_s = Specific gravity
w_n = Natural moisture content I_p = liquid limit A_c = % ash content of dry weight

In this classification system, even though both the ash content and moisture content play a significant role in distinguishing the type of organic soil, the ash content determines the class.

The very high moisture content of most organic soils and non-fibrous peat (which may far exceed 100%) makes them very weak and compressible. Wherever these soils occur, their engineering properties can vary significantly both spatially and with depth. In general, organic soils usually have very low strengths, low dry density and very low hydraulic conductivities (Sabatini et al., 2002). C_c values are high due to their high in-situ void ratios. Some typical properties of organic soils are presented in Table 2.3.

Property	Organic Peat
Moisture Content (%)	650 – 1100
Relative Density	0.1 – 1.8
Bulk Density (Mg/m^3)	0.91 – 1.05
Dry Density (Mg/m^3)	0.07 – 0.11
Void Ratio	12.7 – 14.9
Effective Cohesion (kPa)	20
Effective Angle of Friction (degrees)	5
Shrinkage amount of original volume (%)	10 – 75
Shear strength (kPa)	20 - 30 if drained

Table 2.3: Some Typical Values of Organic Soil Properties (adopted from Bell, 1983; Bell, 1993)

The table clearly depicts the extremely high moisture contents range and very high void ratios, high shrinkage, low density and low drained shear strength of organic soils. The high void ratios result in high compressibility of these soils when subjected to structural loads. As a consequence of these unfavourable characteristics peaty soils pose differential and excessive settlement problems. They also have low bearing capacities.

2.3.3 Expansive Soils

Expansive soils are soils that swell or shrink in direct response to changes in moisture content in the soil. They are probably the most widely spread problematic soils in the world. There are two geological groups of soil (Koerner, 1985) that give rise to volume change namely:

- Soils developed from the chemical decomposition of basic igneous rocks in which the feldspars and pyroxenes weather to form montmorillonite
- Soils resulting from the physical disintegration of montmorillonite bearing sedimentary rocks

Expansive soils are notorious for the damage they inflict on buildings, roads, pipelines and other structures particularly in areas where there is alternating wet and dry climatic patterns which may result in large seasonal changes in the soil moisture content. Jones and Holtz (1973), Jones and Jones (1987), report of an estimated annual cost of damage to these structures in the United States of $9 billion. In the UK the annual cost of damage is $150 million (Gourley et al, 1993).

Expansive soils generally owe their expansive characteristics to the type of clay mineral suites they are composed of. If the low-plasticity kaolinite is the dominant clay mineral, the soil will tend to exhibit a lower shrink/swell potential. Soils that contain the high-plasticity montmorillonite exhibit high shrink/swell potential. Other factors that contribute to the swelling behaviour are related to the engineering properties and the local environment of deposition. Some of the properties of some expansive soil deposits in three different climatic environments namely arid, semi-arid, and temperate zones are shown in Table 2.4. The results are summaries of both field and laboratory tests conducted on expansive soil deposits from various locations in Cyprus, China, Oman, Poland and Saudi Arabia.

The soils presented in the table generally have high to very high liquid limits, high plasticity indices and high activities. The swell potential, where indicated is above 1.0. Even though the clay mineralogy is stated as a major factor controlling expansiveness of clays, this fact can not be substantiated neither is it well defined from the figures provided in Table 2.4 due to gaps in the data presented. The soils generally have low moisture contents except the Nanyang expansive clay.

Property	Expansive soil location/climate				
	Cyprus[A]	Nanyang, China[B]	Oman[C]	Poland[D]	Saudi Arabia [E]
	semi-arid	semi-arid	arid	temperate	arid
Dominant clay mineral	Kaolinite	Montmori-llonite	Montmori-llonite	Kaolinite	kaolinite
w_n (%)	-	21.4	8.9	-	1.3-12.4
w_l (%)	67.8	58.3	50	30-77	32-110
w_p (%)	22.2	26.5	29.5	12-31	12-66
I_p (%)	45.6	31.8	20.5	13-51	8-79
Activity	1.38	-	-	0.5-1.40	0.38-1.04
Clay fraction (%)	33	24.8	20	27-90	21-93
CEC (meq/100g)	18.8	-	70		-
pH	9.4	-	9.2		8.04-9.88
swell potential	-	-	-	>1.5	-
Free swell	-	74.0	-	-	1.7-10.8
Potential expansiveness	-	-	-	M, H, VH	L to H

Table 2.4: Some Engineering Properties of Expansive Clays.

Notes: A, B, C, D, E adopted from Nalbantoglu & Gucbilmez (2001), Miao et al. (2002), Al-Rawas et al. (2005), Kaczyński and Grabowska-Olszewska (1997) and Sabtan (2004) respectively.

L = Low, M = Medium, H = High, VH = Very high

2.3.4 Collapsible Soils

Collapsible soils are generally sensitive to variation in water content, and show excessive volumetric compression under the effects of both wetting and additional loads. These soils usually have an open structure and high voids content. They are free draining and unsaturated. Loess and the red coffee soils are typical examples of collapsible soils. The characteristics of loess shown below are used to represent some of the properties of collapsible soils.

According to Bell (1993), loess deposits have 50-90% of their particles in the silt size range and sandy, silty and clayey varieties can be distinguished. The engineering behaviour of loess is affected by whether the loess is sandy, silty or clayey. The silty variety is characteristically extremely erodible whereas the sandy and clayey types are collapsible but less erodible than the silty variety (Sabatini et al, 2002). The undisturbed densities of loess range from 1.2-1.36 t/m^3. The liquid limits averages about 30% but exceptionally, may be as high as 45%. Their plasticity index ranges from about 4 to 9%, with an average of 6%. Loess generally has low SPT N-values. The properties of some typical loess of China are shown in Table 2.5.

Property	Loess identification		
	Malan	Lishi	Wucheng
Bulk Density (t m^{-3})	1.34 ± 0.01	1.58 ± 0.015	1.68 ± 0.043
Natural moisture content (%)	4.95 ± 0.19	6.93 ± 0.554	7.48 ± 1.009
Coefficient of Permeability (10^{-5} cms^{-1})	40.72 ± 5.45	5.36 ± 0.884	1.472 ± 0.554
Effective cohesion (kgf cm^{-2})	0.31 ± 0.094	0.54 ± 0.052	0.53 ± 1.391
Coefficient of collapse (%)	9.55 ± 1.965	0.75 ± 0.28	0.02 ± 0.005

Table 2.5: Some Geotechnical Properties of Loess Deposits of China (after Derbyshire, 2001)

2.4 Applications of Ground Improvement

The reasons for the application of ground improvement are numerous and depend on the type of facility. Department of The Army (1999) summarizes the various reasons to include mitigation of excess deformation or differential settlement, reduction of settlement, stabilization of dispersive, collapsing or expansive soils, increase resistance to liquefaction and improvement of properties of poor foundation materials to mention a few.

Facilities that may require ground improvement include

- Embankments (highways and dams)
- Levees
- Slopes (excavations)
- Buildings
- Tanks
- Locks
- Tunnels

and many others. The first three constitute earth structures which CUR (1996) divides into two categories, namely those

- that impose load on the subsoil such as dams, road and rail beds, general land fills, banks and depots for soil and waste and
- which relieve the subsoil of load for example water courses, river widenings, harbours, excavations for roads and rail lines, building excavations (deep basements) and trenches.

The first category structures would suffer settlement and bearing capacity problems on a soft soil foundation for example, while the second may encounter stability problems on the same foundation. Figure 2.1 illustrates a typical embankment on soft ground clearly showing the variations in engineering design drawings and the real field performance. The development of any such facility on a soft ground would call for appropriate ground improvement programmes bearing in mind the magnitude and the time for settlement of the embankment.

Figure 2.2 illustrates the type of problem that an excavation will pose to the intended structure assuming the excavation is in a homogeneous material employing the well-documented rotational slides failure mode typical of homogeneous materials. The failed mass is characteristically slumped in the toe area of the slope.

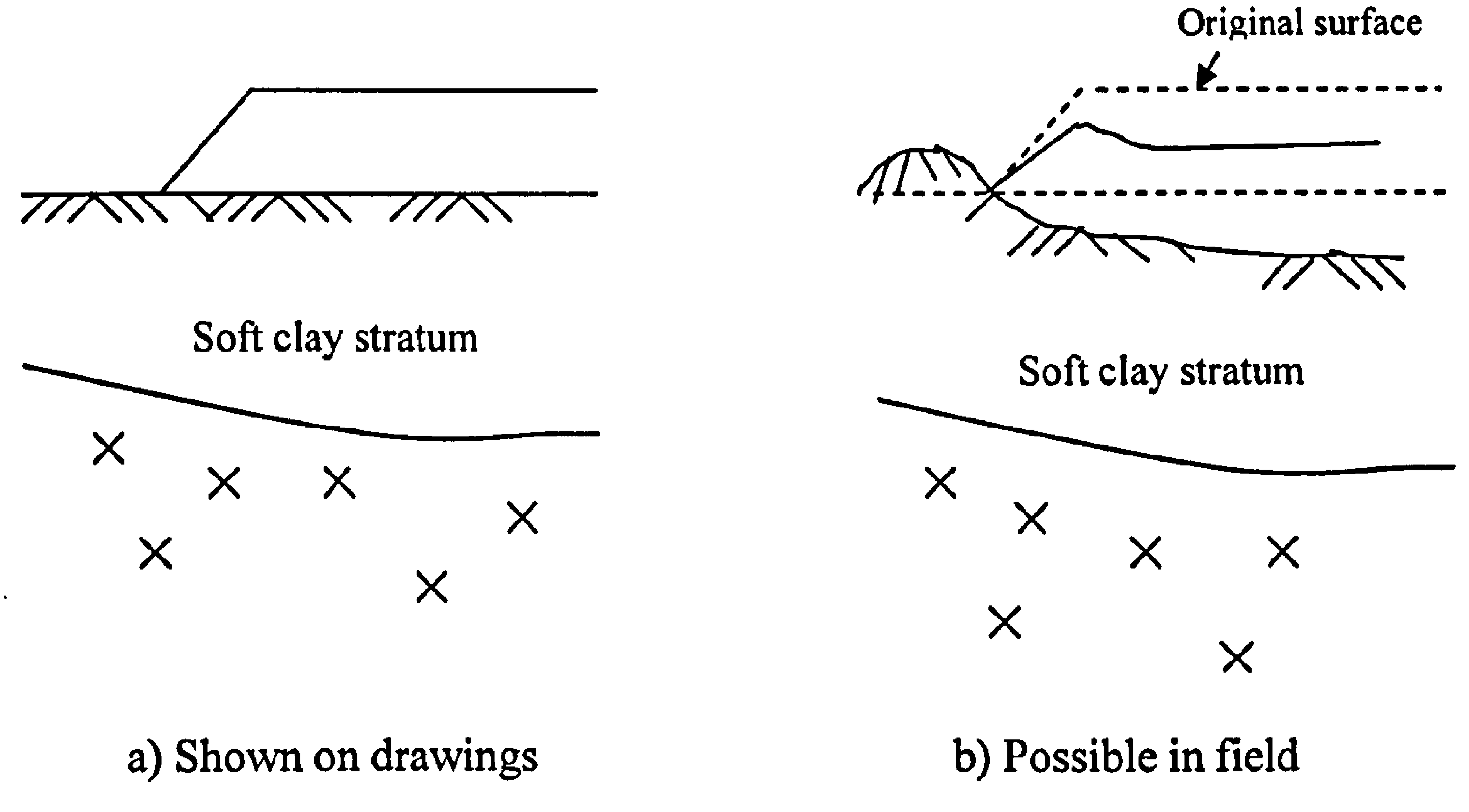

Figure 2.1: Embankment on Soft Ground (after Dibiago and Myrvoll, 1981).

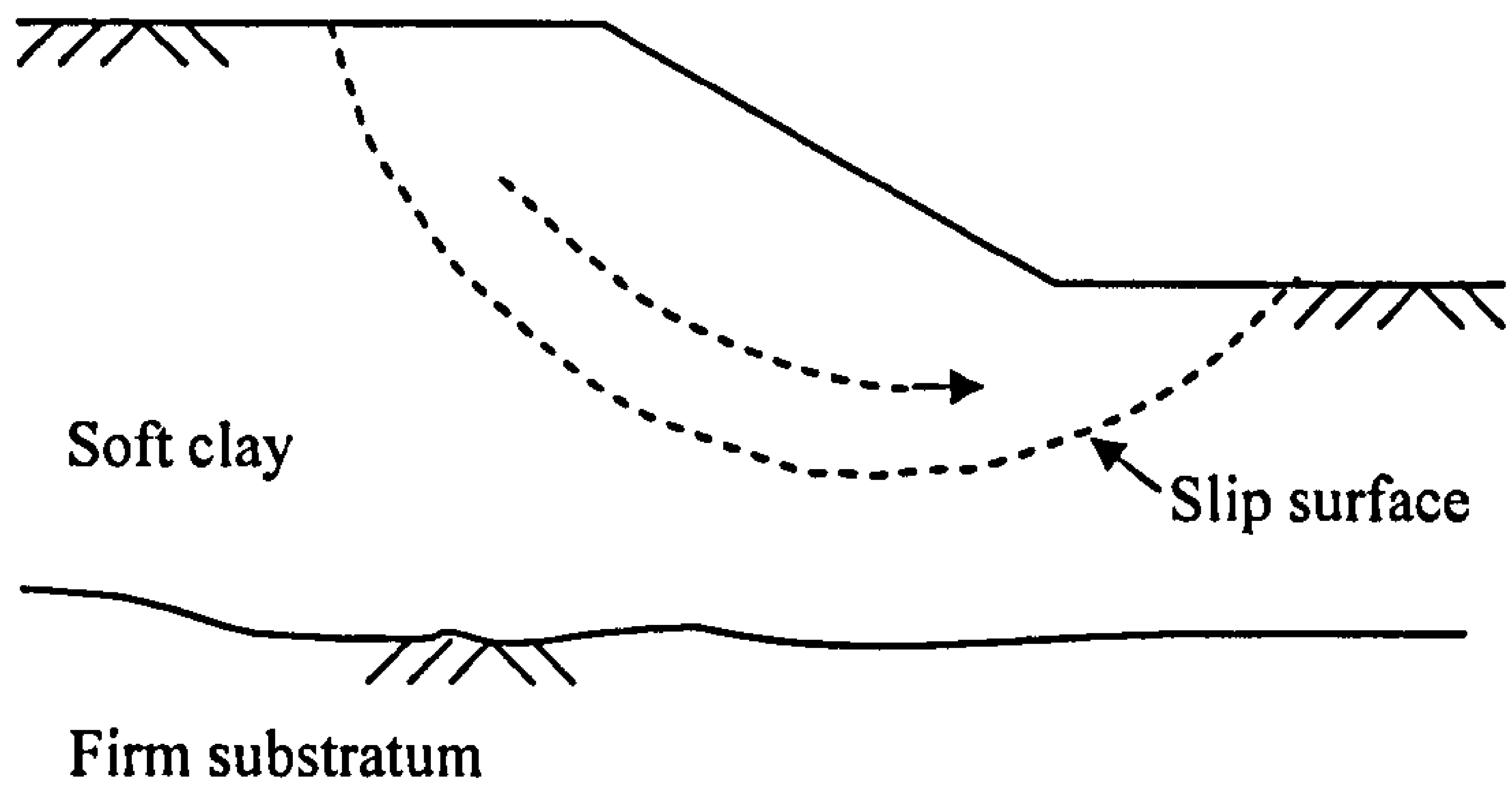

Figure 2.2: Base Failure Typical for Clay Slopes Underlain by Deep, Hard Substratum (after McCarthy, 1993).

Ground improvement techniques for the solution of this type of problem will aim at prevention of failure of the slope. However, before the implementation of any ground improvement scheme, an assessment of the need for ground improvement for the facility must be carried out (Department of The Army, 1999).

2.5 Ground Improvement Technologies.

A lot of soil improvement techniques are in use today as a common construction practice in many parts of the world. The methods range from the traditional surface compaction of soils to the use of admixtures such as lime and also inclusions as a means of reinforcing the soil. The International Society for Soil Mechanics and Foundation Engineering Technical Committee 17 (ISSMFE TC-17) classification of the different ground improvement techniques is given in Table 2.6.

In this classification system the methods are divided into three major categories namely: ground improvement, ground reinforcement and grouting and admixture methods.

Methods that fall under the ground improvement category are mainly the traditional or conventional ground improvement techniques that are applied to modify the characteristics of the poor soil deposit. The term "traditional or conventional ground improvement techniques" is used to describe the methods of ground improvement in which sufficient knowledge about these methods is known with precision in their modes of application to ensure the absence of errors. Thus these methods are the most commonly used. Examples of this group of improvement techniques include the preloading, vibro compaction and drainage techniques.

1) Ground improvement • Dynamic Deep Compaction • Vibro Compaction • Vacuum Consolidation • Drainage • Preloading • Blasting • Heating • Ground Freezing • Vibro-replacement Stone Columns • Vibro-Displacement stone columns • Lime columns • Electro-Chemical • Environmental ground modifications **2) Soil Reinforcement** a) Engineered Fills • Reinforced Soil Steel • Mechanically Stabilized Earth Structures (MSE) • Geosynthetics • Fibre Reinforcement • Natural reinforcement	b) Ground Reinforcement • Soil Nailing • Micropiles • Soil and Rock Anchors **3) Grouting and Admixtures** a) Grouting • General Grouting • Permeation Grouting (chemical, microfine cement, bentonite, others) • Compaction Grouting (displacement) • Jet Grouting (replacement, erosion) • Slurry Grouting (intrusion) • Fracture Grouting (soilfrac) and other techniques b) Mix in place • Admixture and Shallow Soil Mixing (SSM) • Deep Soil Mixing (Slurry) • Deep Soil Mixing (Dry) 1) Dry Jet Mixing (DJM) 2) Lime Cement Columns (LCC) • Slurry walls

Table 2.6: ISSFME TC-17 Soil Improvement Classification (after Juran and Levy, http://tc17.poly.edu/ikd.htm, 27/09/01).

The reinforcement techniques encompass all those techniques that involve the construction or inclusion of elements in the ground with the main benefit resulting from the structural aspects of the elements themselves and not improvement of the surrounding soil properties. There is a further subdivision of this group of methods into engineered fills and ground reinforcement methods depending on whether the method is applicable to fill materials (for example, mechanically stabilized earth structures) or to reinforcement of the ground as a whole as in the case of micropiles. Included in the grouting and admixture techniques are the grouting methods such as jet grouting, permeation grouting and fracture grouting and the mix in place methods such as deep soil mixing and shallow soil mixing.

The ASCE Soil Improvement and Geosynthetics Committee (SIG) classification of ground improvement methods (Table 2.7) though similar to the above, shows some significant differences in the groups to which some of the methods belong. For instance, the heating/freezing methods are considered as treatment methods in the SIG system of classification. However these are regarded as ground improvement methods in the later classification by the ISSMFE TC-17. Again, whiles compaction grouting is classified as a ground improvement method in the SIG classification this is regarded as a treatment method by the ISSMFE TC-17. For the purpose of this work these distinctions have not been considered relevant and consequently all the ground modification methods are regarded as ground improvement methods.

Reinforcement	Improvement	Treatment
Stone columns	Deep Dynamic	Soil cement
Soil Nails	Compaction	Lime Admixtures
Deep Soil Nailing	Drainage/ Surcharge	Fly ash
Micropiles	Electro-osmosis	Dewatering
Jet Grouting	Compaction Grouting	Heating/Freezing
Ground Anchors	Blasting	
Geosynthetics	Surface compaction	
Fibre Reinforcement		
Lime columns		
Vibro-Concrete Columns		
Mechanically stabilized earth		
Biotechnical.		

Table 2.7: SIG Committee Classification of Ground Improvement Methods (after ASCE, 1997).

2.5.1 The Common Ground Improvement Technologies

Piling was the most common foundation method for structures constructed on soft clays before modern times. The piles, which were mainly timber, measured up to 7m and were employed to transfer structural load from quays, buildings, embankments and even tunnels to the substratum material with the view to avoiding the soft clay. By 1940 (Flodin & Broms, 1981), the pile length had been increased to between 18 and 20m on the realization of the inadequacy in length of earlier piles. Nowadays, quite a significant number of soil improvement techniques are available and a brief review of some of the applicable methodologies to many problematic soils and in particular soft soil improvement is presented below.

Preloading

Preloading also known as precompression has been widely used to improve the characteristics of soft soils for many years without any change in the method. The technique involves surcharging the ground with a uniformly distributed surface load prior to the construction of the facility (Pilot, 1981) with the aim of reducing the amount of settlement that will occur after construction. The additional vertical stress removes pore water over time and consequent dissipation of pore water reduces the total volume causing settlement. In general the design for settlement reduction is centred on primary consolidation movement using well established soil mechanics principles (Alonso et al, 2000). It is indeed a very economical ground improvement technique but with the disadvantage of time dependency thus delaying construction projects (Juran & Levy, http://tc17.poly.edu/ikd.htm, 27/09/01).

There are two forms of preloading:

1) Overloading
2) Staged construction

In the first, a surcharge (overload), Δq, in excess of the design load, q, (Figure 2.3) is initially placed on the site and removed when the intended facility can be constructed with the occurrence of little or no further settlement. The ratio of the surcharge load to the final load is referred to as the overload coefficient (Pilot, 1981) or surcharge ratio (Bell, 1993). The surcharge required to ensure that settlement, ΔH, will be completed in time, t_2 has to be determined. Leaving the surcharge until time t_2, will give the same amount of settlement as that which would occur under the final load at time t_1.

As the name implies staged construction involves loading the footprint of the proposed structure in stages to gradually increase the shear strength of the underlying soft clay. Precompression is frequently achieved by the use of earth fill, rockfill (to a lesser extent), water filled reservoirs, and vacuum application.

The application of any of these loading methods may have certain limitations. Chu et al (2000) indicate the inappropriateness of the use of a high embankment fill on soft clay during the construction of an oil storage station in Tainjin, China in comparison to the use of vacuum preloading. The high embankments apart from the requirement of the use of large volumes of fill material also created instability problems. In the case of water filled reservoirs, one would not consider this approach as appropriate in areas with scarce supply of water.

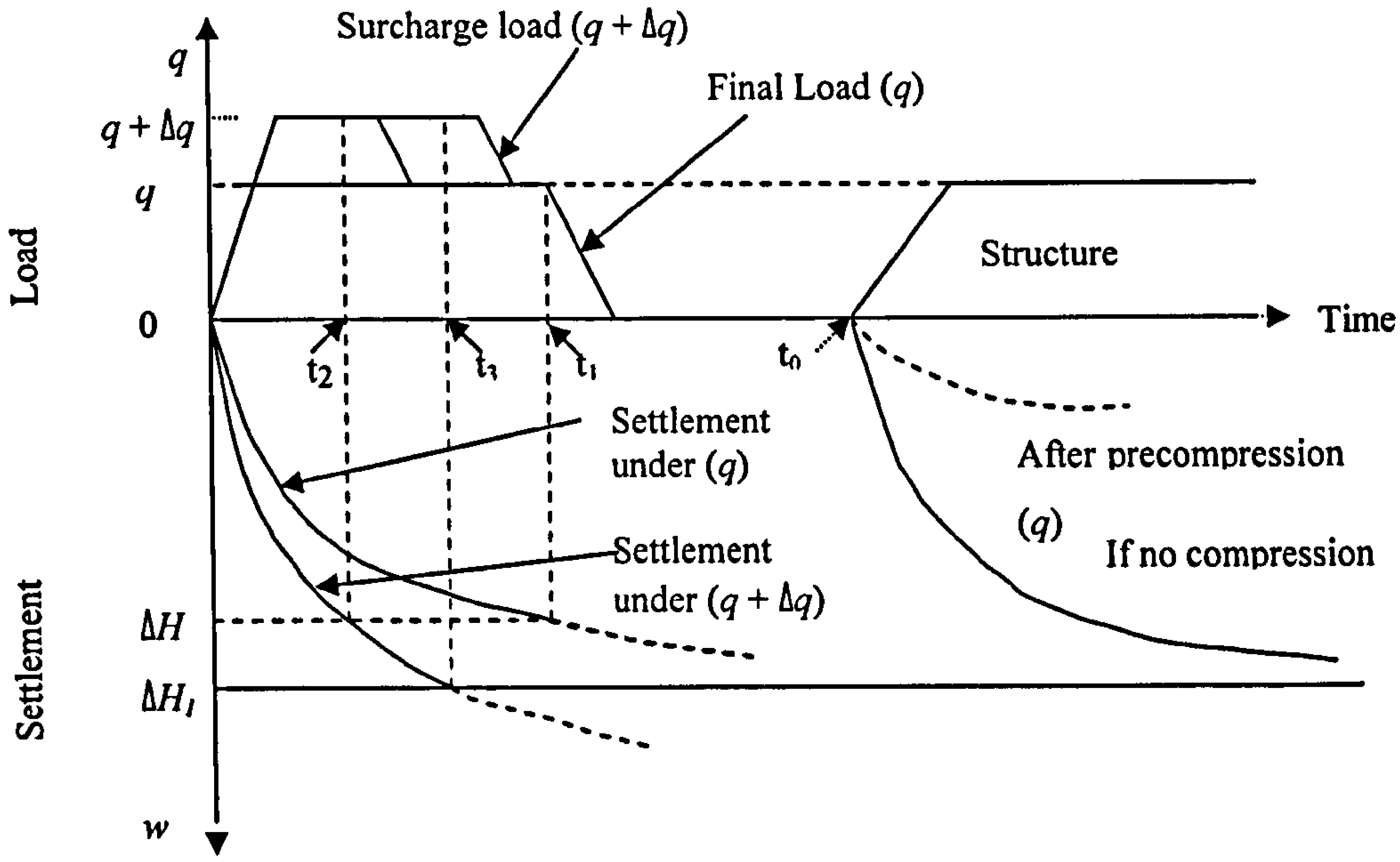

Figure 2.3: Principle of Precompression using Surcharge Loading (Adopted from Bell, 1993).

Even though precompression is focused on reduction of settlement due to primary consolidation, Alonso et al. (2000) have shown that preconsolidating the soil is also an effective way of reducing secondary settlements to acceptable levels. They observed a sharp reduction in the secondary compression coefficient with only small degrees of overconsolidation thus substantiating Koutsoftas et al. (1987), and Yu & Frizzi (1994) views on the significant reduction of secondary compression deformation of soils overconsolidated to moderate degrees. Bell (1993) has observed that the rate of secondary compression appears to decrease with time logarithmically with its value in direct proportion to the compressible layer thickness at the start of secondary compression.

Due to time constraints, the practice of precompression is limited to relatively thin layers and to soils that compress rapidly (Bell, 1993). Very often precompression is usually carried out in conjunction with vertical drains so as to accelerate settlement.

A relatively large area is required for this method of ground improvement to be feasible. Because the method is carried out by using fill material, the cost of applying this method is dependant largely on the haulage distance of fill material thereby necessitating the reliance of its use on the availability of local supply of fill.

Vacuum Preloading

The method of vacuum preloading was introduced by Kjellmann in 1952 and has proven to be an effective means for improvement of saturated soft soils. Vacuum preconsolidation has been extensively used for consolidation of soft, highly compressive soils (Ye et al., 1983; Choa, 1989, Qian et al., 1992; Harvey, 1997; Bergado et al., 1998, Shang et al., 1998; Shang & Zang, 1999; Chu et al., 2000 and Tang & Shang, 2000), land reclamation (Shang et al., 1998) and consolidation of soda ash tailings, (Shang & Zang, 1999). Table 2.8 illustrates the varied nature of the type of facility for which the ground has been improved by the vacuum preloading method in some Asian countries.

The method is gaining more popularity over preloading by surcharge only technique due to its acceleration of the consolidation process. Out of 99 ground improvement case studies, Juran and Levy (http://tc17.poly.edu/ikd.htm, 27/09/01) have shown that 13.13% of the number of projects were performed using the vacuum consolidation method whiles only 6.06% of this number were carried out using the preloading technique. A comparison of the two methods on a pilot scale at the Yaoqiang airport project China indicates that the same level of consolidation was obtained by the use of the vacuum consolidation technique on the same soil profile in 50 days as compared to a time of 90 days when only the surcharge loading was applied (Tang and Shang, 2000).

From Table 2.8 it is observed that a good reduction of settlement is obtained with significant increases in the bearing capacities of the soils. In general however the estimated settlements are far above the achieved settlement. The different soil types treated include silt, clay and peat. Variations exist in the areas of treatment indicating there may not be limitations in terms of area. There is a significant difference in the thickness of the formations treated in the above examples. Thickness of 16m recorded for the Tanjin New Harbour and the Tianjin, Oil Storage facility in China indicate that the method can reliably be employed for the improvement of some thick problematic soil deposits.

Project	Tanjin New Harbour	North-east New Railway Line	Factory	Oil Storage Station	Yaoqiang Airport
	Nagaraj & Miura (2001)			Chu et al. (2000)	Tang & Shang (2000)
Location	China	Japan	Lianyungang, China	Tianjin, China	Jinan, China
Soil description	Silty clay	Peat & Silt	Marine clay	Marine clay	Soft Clay
Water Content (%)	55	580-860	69 –85	25 – 55	34
Void ratio	1.4	-	1.62-2.36	0.75-1.50	0.94
Unit weight (kN/m^3)	17	10.30	15.11-5.79	16.5-19.5	18.80
Initial Shear strength (kPa)	16.7-20.6	3.4-5.9	5.7-19.6	7.5-40	-
Treatment area (m^2)	1250	1950	4000	50000	145000
Thickness (m)	16	13	10	16	4
Degree of vacuum (kPa)	80	93	86.7	80	80
Increase in shear strength (kPa)	131-190	186-190	170-440	30-80	-
Increase in bearing capacity (%)	300	200-300	250	200-300	-
Estimated settlement (mm)	811	2040	1000	-	133
Measured settlement (mm)	565	1490	700	1000	210
Reduction in settlement (%)	69.5	73	70	-	-
Degree of Consolidation (%)	-	-	-	>80	77.4
Depth treated (m)	-	-	-	20	14

Table 2.8: Cases of Vacuum Preloading

The method should however be used with caution due to reported cases of crack development in the adjacent area of the application (Chu, et al, 2000, Tang and Shang, 2000). The cracks are mainly a result of lateral movement of the soft soil towards the point of application of the vacuum. Existing facilities in the area may therefore be adversely affected. The extent of crack development therefore should be evaluated prior to start of the programme. Field tests may therefore be essential before implementation of the programme.

Vacuum preloading is normally carried out by sealing the treatment area with an airtight membrane keyed into an anchor trench surrounding the area and creating a vacuum underneath it by means of vacuum pumps. As the vacuum is applied to the soil the soil pore water pressure is drawn down. If the total stress remains unchanged, this decrease in pore pressure increases the effective stress in the soil and consolidation, with the consolidation process being similar to that achieved by preloading. This method has been found to be particularly suitable for very soft soils where instability problems may arise due to surcharge (Bell, 1993) and can provide an equivalent preloading of about 4.5m high conventional surcharge fill (Juran & Levy, http://tc17.poly.edu/ikd.htm, 27/09/01). In areas where the availability of fill material is questionable, vacuum preloading is most suitable. It also eliminates the risks of failure, as may be the case with preloading and accelerates consolidation. Where porous material overlies the soft soil stratum, vacuum preloading may not be efficient due to leakages.

Vacuum preloading is invariably carried out in conjunction with vertical drains thus further lowering the hydraulic head and increasing soil strength.

Vertical Drains

The vertical drain technique has been widely used in the construction of embankments and reclamations over compressible soils as a means of accelerating consolidation in these soils. The method is most suitable for very thick soft clays and under situations of exceptionally low permeability in which case preloading the soil will prove inadequate due to the length of time significant compression will be achieved. Their installation shortens the drainage path under which the clay will consolidate. However, there have been situations where the drains have failed miserably to promote the necessary rapid consolidation of the soil under load. According to Van Impe et al. (1997a) vertical sand drains are generally used for small jobs and in harbour areas in Belgium.

The traditional vertical drains were sand columns installed mainly by means of closed-ended mandrels (which caused thick smear around the drains), jetting, boring or displacement techniques. These are preferably replaced with prefabricated band drains produced from polyethylenes, PVC, polypropylenes and polyesters, due to technological advances and the rising costs of providing large quantities of suitable sand for the drains.

Literature abounds on the technique (Atkinson & Eldred, 1981; Hansbo, et al., 1981; Nicholson & Jardine, 1981, Bergado et al, 1996a; Almeida, et al, 2000; Nash, & Ryde, 2000) and used in conjunction with preloading and vacuum preloading (Tang & Shang, 2000; Chu, et al, 2000).

The design of vertical drains has been based on the Terzaghi's consolidation equation in which Terzaghi (1943) proposed that the time taken for a given soil to attain a certain degree of primary consolidation varies directly with the square of the longest drainage path. The three-dimensional process of consolidation is simplified to a one-dimensional movement resulting from a combination of both vertical and radial flow to the drain. Setting up a regular pattern of vertical drains permits both radial and vertical flow of water from the soil to the drains significantly reduces the time taken for consolidation, than if only vertical flow were operating. It must therefore be emphasised that the drain spacing has an undoubted effect on consolidation. A spacing of 1.5 – 5.0m of sand drain columns is reported in the literature (Hunt, 1986; Bell, 1993) installed in square or triangular patterns. It is further indicated that the effectiveness of sand drains in soil improvement is influenced by drain spacing than by drain diameter.

Generally, the depth of treatment is taken to the entire thickness of soft soil. However McGown & Hughes (1981), suggest that installation of sand drains to depths beyond 20m may be uneconomic.

The various assumptions made in the theories for design of vertical drains include the homogeneity of the soil, variations with time of the permeability and coefficient of consolidation of the soil, an appropriate hydraulic flow law, drain effects such as smear, disturbance and well resistance, the loading rates and creep effects.

Several types of drains are available (Sand Drains, Band Drains, Sand Wicks, Prefabricated Vertical Drains). The performance of the drains is affected by make and method of installation (Figure 2.4). The selection of one type should be based on discharge capacity, economic aspects and their performance in service for overall effectiveness in soil improvement.

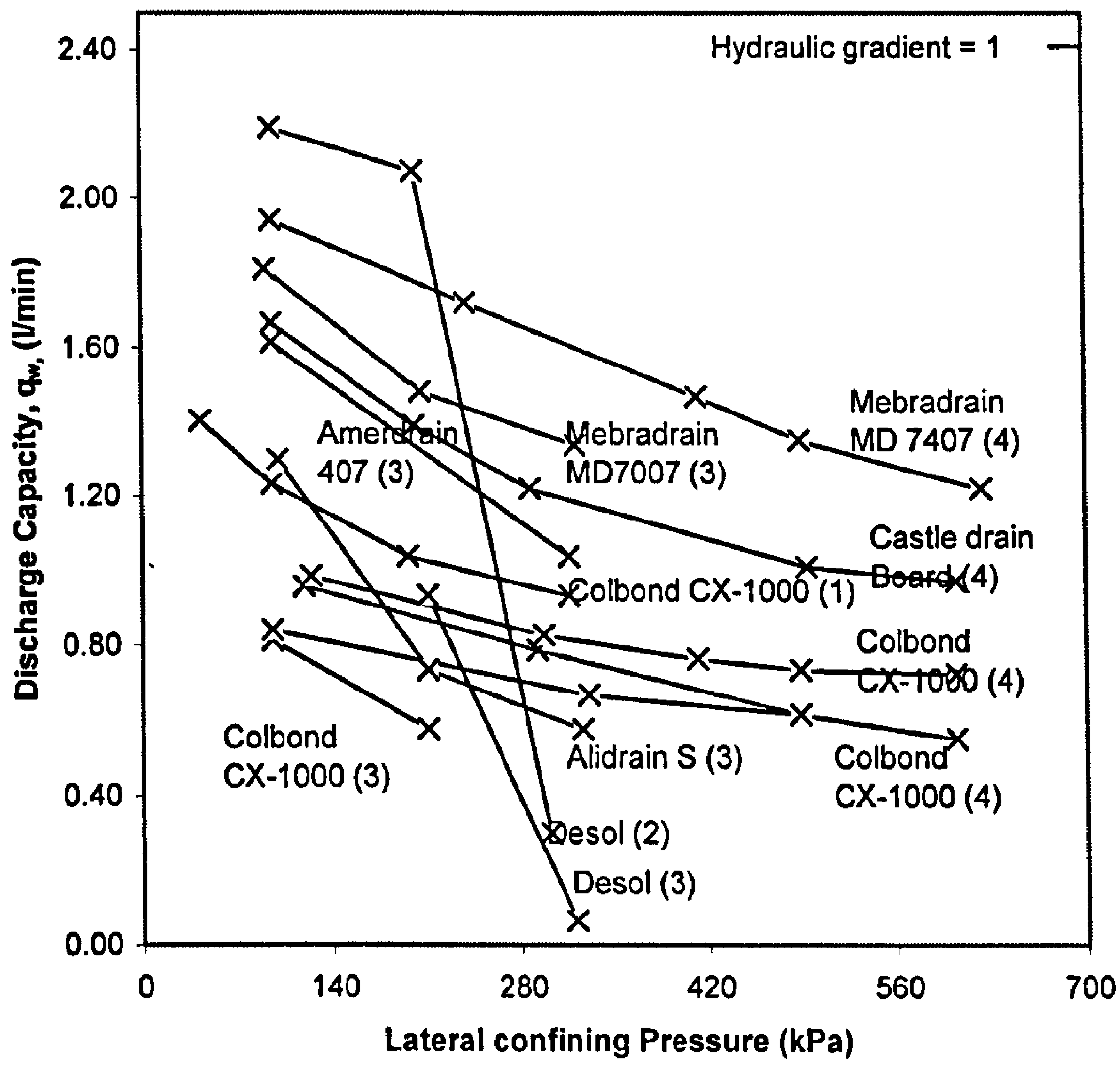

Figure 2.4: Typical Values of Vertical Discharge Capacity (after Rixner et al., 1986)

Band drains without open channels in their central area for instance may have a lowered discharge with time due to clogging by fines though they may be cheap. Indeed the method of installation can have considerable effect on performance of the drain as it can reduce the smear effect. Bergado et al. (1996a), based on laboratory studies and analysis on Prefabricated Vertical Drains (PVD) from various manufacturers, observed an almost linear decrease in discharge of these drains with increase in lateral pressure, time and hydraulic gradients. Discharge capacity also decreased considerably depending on make and under various degrees of bending of the drains and up to 78% for 30% bending with two clamps PVDs. Installation of PVDs must therefore be carried out with extra attention or supervision to eliminate or minimize folding.

Prefabricated vertical drains also called wick drains are typically installed in soft, cohesive soil deposits to increase the rate of consolidation and corresponding strength gain. They have the added advantage of liquefaction mitigation by improving drainage and/or adding reinforcement (Department of The Army, 1999).

Table 2.9 (after Juran and Levy, http://tc17.poly.edu/ikd.htm 27/09/01) shows estimates of cost of installation of vertical drains for three types of projects. From the table, there is considerable savings in cost as project size increases.

Project size	Length of drains (m)	Cost per linear meter (US$)
Small	3000 -9000	0.20 – 0.50
Medium	9000 - 45000	0.14 – 0.27
Large	>45000	0.09 – 0.18

Table 2.9: IKDGIT Costing of Vertical Drain Installation (after Juran & Levy, http://tc17.poly.edu/ikd.htm, 27/09/01).

Stone Columns

The use of stone columns as a ground improvement technique in soft clay foundations dates back to the 1960s. A stone column is described as an excavated vertical cylindrical hole in the soft soil layer filled with compacted crushed rock fragments and gravel to form columns or 'piles' confined by the soil. Stone columns are only one of the columnar inclusions (granular piles, sand compaction piles, lime or cement columns etc) techniques for ground improvement. They serve as vertical drains hence reduce excess pore pressures caused by rapid loading or earthquakes, increase the bearing capacity, reduce settlement, and improve stability and resistance to liquefaction. Stone column use is limited to soils with undrained shear strengths of less than $14 kNm^{-2}$ (Bell, 1993). Indeed the technology is an alternative support system to deep foundations (piling).

Stone columns often measuring between 75cm and 150cm in diameter are constructed to completely penetrate the weak strata to the underlying bedrock or a hard layer. It is however not uncommon for floating columns to be installed. For any project a large number of columns are usually installed in a uniform and equally spaced pattern.

FHWA (1983) indicates an equilateral triangular pattern gives the most dense packing. Each column acts within a cylindrical cell with radius of influence *b*. Center-to-center column spacings of 1.5 – 3.5m are typical.

Poorooshasb and Meyerhof (1997) have shown that column spacing plays a major role in column performance and conclude column spacing larger than 4 diameters makes the system inefficient even under the most favourable conditions. Column length and diameter however, have little or negligible effect on the performance of the column system but very short length columns (≤5m) have the likelihood of failing at higher settlements by the formation of shear bands. They also found that the degree of compaction of the material in the columns also greatly affects column performance as it controls column strength, stiffness and dilatation.

A number of works (Baumann and Bauer., 1974; Hughes and Withers, 1974; Poorooshasb and Meyerhof, 1997) show that several factors relate the bearing capacity and deformation behaviour of stone columns including:

a) The shear strength of the in-situ soil.
b) Lateral stress within the soil
c) Radial pressure/deformation characteristics of the soil
d) Angle of internal friction of the backfill
e) Column diameter.

Analysis of stone column behaviour is carried out by the conceptual unit cell approach. Stress concentration occurs in the stone column upon placement of the intended structure over it. This is accompanied by reduction in stress in the surrounding less stiff soil as the vertical settlement of the stone column and the surrounding soil is approximately the same. Stress concentration occurs in the stone column for it been stiffer than a cohesive or a loose cohesionless soil. The following relations give the stress due to an applied loading in the stone column and the surrounding soil.

$$\sigma_c = \sigma/[1 + (n - 1)\, a_s] = \mu_c \sigma \tag{2.1}$$

and

$$\sigma_s = n\sigma/[1 + (n - 1)\, a_s] = \mu_s \sigma \tag{2.2}$$

where

σ_s = stress in stone column

σ_c = stress in surrounding soil

σ = average stress

μ_c & μ_s are the ratio of the stress due in the clay and the stone column respectively to the average stress

a_s = area replacement ratio

n = stress concentration factor

Alamgir et al. (1996) have shown remarkable decrease of shear stress along column – soil interface with depth especially for close spacing of columns. Their work indicates shearing stress is developed only at the upper one third of the column system with the remaining two thirds of the column almost shear stress free. A phenomenon they attribute to arching of the soil between the upper sections between the columns which prevents transmission of forces to the lower portions. Notable variations in magnitude of stress concentration with depth and radial distance depending on the column spacing and relative stiffness of the column and the surrounding soil were also observed. In a related study on model tests, Muir Wood et al. (2000) noticed that load transfer to the base of stone column ceases beyond a certain length of the column as a result of the total shedding of load through shaft friction.

A group of stone columns in a soft soil is thought to undergo a combined bulging and local bearing type failure (FHWA, 1983). Local bearing failure occurs by punching of the relatively rigid stone column (or group) into the surrounding soil whereas column groups with short column lengths undergo end - bearing failure. Bearing capacity failure of individual stone columns may also occur.

A very common method of installation of stone columns is vibroflotation, where with a vibrator mounted at the lower end of a steel tube the probe is inserted into the ground while jetting with water or air. The gravel or stones normally placed adjacent to the vibrator sink from the ground surface to the bottom of the hole created. Good quality stone columns installed in this way in very soft soils require considerable experience (Van Impe et al., 1997b).

Lime Piles and Columns

These are cylindrical columns formed in clay soils by mixing the clay with unslaked lime. Lime columns act as vertical drains due to their high permeability as compared to the surrounding clay as well as reinforcing the soil. They are used for two distinct purposes namely, to improve the bearing capacity of soft soils and stabilization of slopes. In the first instance there is significant reduction in the water content of the soil. This densifies the soil and consequently increases its strength and stiffness. In the second application it is intended to cause ion migration and subsequent lime-clay reaction in the surrounding soil.

In lime treatment, modifications occur within 24-72 hours after application on the basis of cation exchange followed by a reaction with the siliceous components of clay to bring about stabilization. The installation of lime columns therefore shortens construction time.

It is documented (Rogers & Glendinning, 1997) that lime pile usage for slope stabilization has been in long practice in the USA, Thailand, Sweden and Australia and also in China, Japan and Russia as a ground improvement technique for soft soil. A considerable volume of literature exists on the stabilization mechanisms of lime columns (piles). Though diverse in context Rogers & Glendinning (1997), categorize them under two broad themes namely:

- A combined pile expansion and clay dehydration (applicable to bearing capacity and settlement characteristics improvement)
- The migration of calcium ions from the pile into the surrounding clay and its subsequent stabilization by lime - clay reaction.

The fundamental stabilization mechanisms according to Rogers & Glendinning (1997) are:

1) Lateral consolidation of the surrounding ground due to a small net volume loss from the hydration reaction of quick lime according to the equation

$$CaO + H_2O \longrightarrow Ca(OH)_2 \qquad (2.3)$$

(Water drawn out from between the soil particles for this reaction causes densification).

2) Water content reduction.
3) Clay-lime reaction.

4) Reduction in pore water pressure (addition of quicklime to soil causes negative pore water pressures that draw in water to the piles to react.
5) Consolidation of the shear zone (negative pore water pressures cause consolidation of clay in remoulded shear zone of a failed slope).
6) Pile strength (this provides an increase in the bearing capacity).

Deep Dynamic Compaction (Dynamic Consolidation)

This method in its initial stages of introduction was applicable to ballast fills and granular soils but has now been applied to a variety of soils ranging from organic and silty clay to loosely packed coarse grained soils and fill and even soft clays. It involves the dropping of heavy weights on the ground surface with the view of densifying the soil at depth. Depths of densification could be between 10 – 30m but in general the depth of influence is controlled by the impact energy, damping properties of the soil, the shape of tamper, proportion of gas in the soil voids and dissipation of pore water pressure (Bell, 1993). Where depth of densification is high the method is termed deep dynamic compaction. The weights vary from 10 – 30 tons with drop heights of between 15 – 40m. Impacts are carried out at the centres of 2 x 2m to 6 x 6m square grids.

Deep Dynamic Compaction has found application in situations where reduction of foundation settlement and seismic subsidence is required. It is also applied to induce settlement in collapsible soils, densify garbage dumps, improve mine spoils and to permit construction on fills.

Geotechnical parameters to consider are basically the soil conditions, groundwater level, the relative density, degree of saturation and permeability.

Menard and Broise (1975) found soft clays amenable to application of the method due to the following reasons.

- Soft clays (indeed most quaternary soils) contain varying small proportions of gas up to 4% in the form of micro-bubbles whose equilibrium is modified under vibration.

- Under repeated impacts the gas compresses and at the saturation energy liquefaction of the soft clay occurs.

- The impacts create vertical fissures resulting in an increase in permeability of the clay. Again increase in permeability occurs due to liquefaction and decrease in intergranular stresses.

- There is thixotropic recovery during the tamping operation as a consequence of shear strength reduction in the initial stage.

They, however, observe that large vibrations that are associated with the method makes it unsuitable in built up areas and recommend a minimum clearance distance of 30m from existing structures. A vibration sensitivity analysis is thus necessary prior to start of work to give an idea on the effects that the method will have on any established structures.

Quite a good number of tamping devices are available. Jessberger and Beine (1981) on the basis of laboratory studies on fine sand and silt evolved design charts for the choice of the fitting mass, height of fall and base area of the falling weight. Earlier, Menard had shown that impact devices with extremely high energy of impact could compact to depths many times the diameter of a wide impacting mass achieving significant densifying action on certain soils in their saturated state.

The implementation of the dynamic compaction programme relies heavily on experience rather than theory for soft clays in particular (Menard and Broise, 1975; Pilot, 1981). The use of heavy impact equipment makes the method a rather expensive ground improvement technique in remote regions.

Dynamic compaction is accomplished by successively impacting the soft ground surface by dropping a heavy weight from great heights of up to 40m. The blows are concentrated at specific locations while keeping the distances between the centres of tamping ranging from 4 - 20m. Usually a grid pattern is set out. Each successive impact imparts some energy into the soil, causes some amount of immediate volumetric strain thus generating some excess pore pressure. The level of energy input into the system is termed the 'saturation energy' when the pore pressures equal 100% liquefaction pressure. At this stage imparting additional energy to the soil never results in any further volume change.

The depth of improvement (D) of the in situ soil as a function of the impact energy as proposed by Menrad & Broise (1975) is given by the following relation.

$$D = n\sqrt{Wh} \quad \textbf{(2.4)}$$

Where W = weight of pounder (tonnes)

h = initial height (in metres) of the pounder.

n is a constant depending on the type of material.

Qian (1985) proposes $n = 0.66$ for soft clays. As a simple rule-of-thumb however n is usually taken as 0.5.

Incorporating the several parameters that control the depth of influence such as soil type, site characteristics, surface area and shape of pounder, number of blows and number of passes, grid spacing, ground water conditions etc, and not only the energy per blow ($E_d = W_h$), Charles et al. (1981) proposed

$$D = 0.4\left[\frac{E_d.B}{A_p.C_u}\right]^{0.5} \quad (2.5)$$

Where A_p = surface area of pounder,

B = energy applied per unit area of the pounder and

C_u = the undrained strength of the soil.

An exhaustive analysis by Mayne et al. (1984) suggests the attainable treatment depths vary according to the initial strength, soil type and energy input (Figure 2.5). For the same energy input, a greater depth of improvement is achievable for loose or weak soils as compared to stiff or dense soils.

Dynamic compaction improves the in situ properties of the soil however; prediction of the degree and extent of soil improvement is always not possible at the site. Initial trials are therefore often carried out so as to determine the efficiency and extent of the improvement.

The method is not recommended for soils with clay contents greater than 15%. The permeability of such a soil according to Van Impe & Madhav (1995) will be too low to allow rapid dissipation of excess pore water pressures. The technique is suitable for the treatment of large areas very quickly.

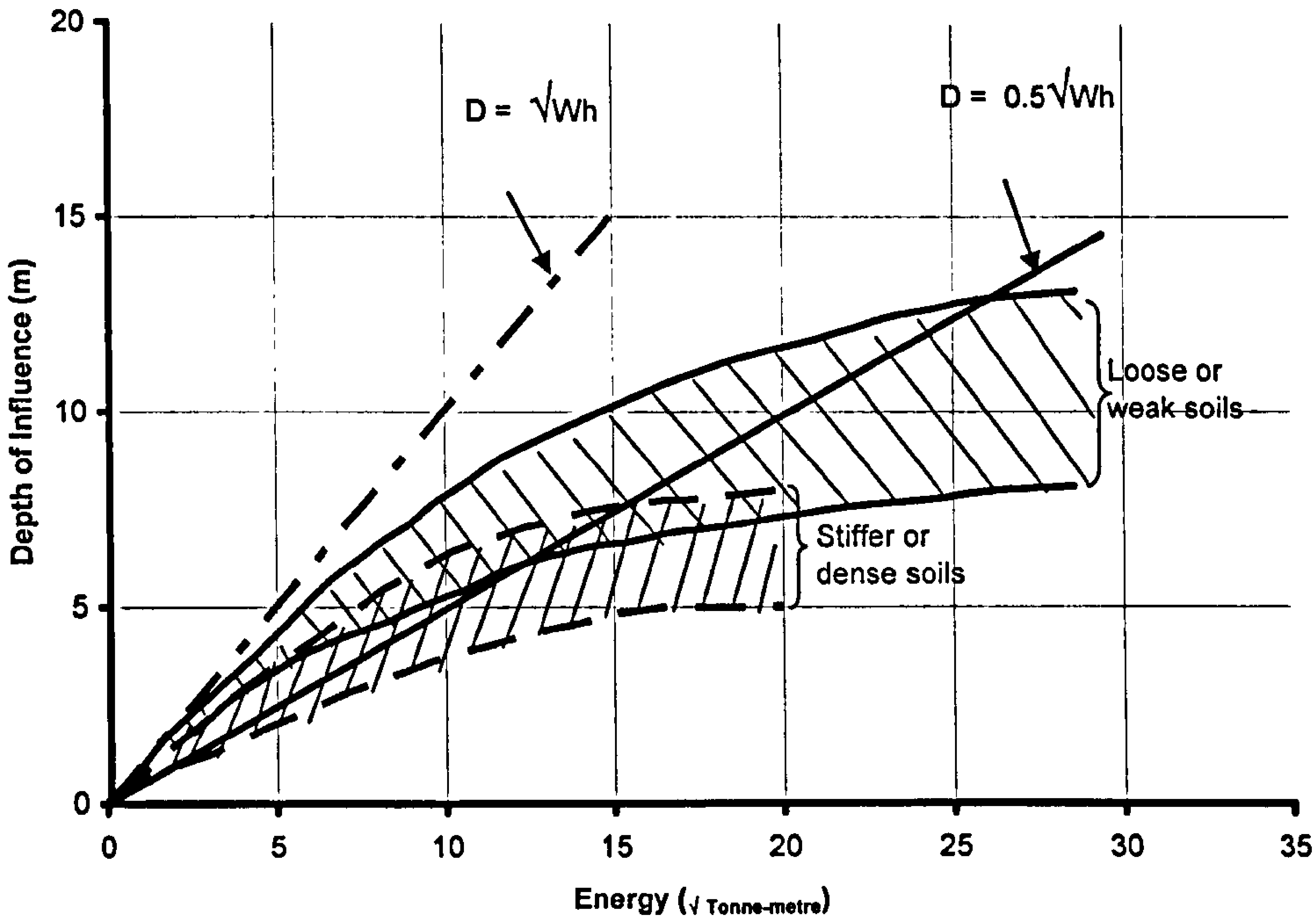

Figure 2.5: Depth of Treatment

Soil Improvement by Use of Additives

Lambe (1962) describes soil stabilization as the alteration of any soil property to improve its engineering performance. Alteration is usually obtained by the use of additives (chemicals or other materials). In the past, clay-gravel mix was the only stabilization method particularly for pavement construction. Nowadays additives employed include cement, lime, fly ash, bentonite, asphalt and salts (calcium and sodium chlorides), the first two being predominant. Mixing additives with soil results in remarkable improvement in volume stability, permeability, strength and stress-strain properties and durability of the soil under consideration. Bell (1993) states the high strength and stiffness developed result from void space reduction, bonding together of particles and aggregates, the maintenance of a flocculent structure and prevention of swelling. Indeed, the achievement of quality results therefore requires good mixing of the stabilizers with the soil.

a) Cement Stabilization

Soft soils and indeed any type of soil with the exception of highly organic soils or some highly plastic clays, can be chemically improved by adding cement as an alternative to mechanical type ground improvement techniques such as vertical drains. The addition of small amounts of cement up to 2% modifies the properties of the soil while large quantities cause radical changes in these properties (Bell, 1993). Cement stabilization was preferred in granular soils because they pulverize and mix more easily than fine-grained soils; however Deep Cement Mixing (DCM) has of recent become a popular ground improvement technique in soft clays to increase the bearing capacity and reduce settlement. The technique has been used for many diverse applications to include building and bridge foundations, retaining structures, liquefaction mitigation, temporary support of excavation and water control in many countries particularly Japan, Taiwan and the USA.

Ordinary Portland cement is commonly used as a hardening agent. The reactions that take place (Saitoh et al., 1985) include:

- Hydration of the ordinary cement producing $Ca(OH)_2$.
- Adsorption of $Ca(OH)_2$ by clay (or cation exchange reaction) until the clay is saturated with $Ca(OH)_2$ and thereafter,
- Pozzolanic reaction between clay and $Ca(OH)_2$.

The strength characteristics of the hardened soil bodies are governed by $Ca(OH)_2$ adsorption and the pozzolanic reactivity of the soils. Indeed variations in the effects of the improvement on clay soils bear direct relations to the clay mineralogy. For instance the addition of cement results in small increases in the compacted densities of kaolinitic and illitic clay soils while the opposite occurs in montmorillonitic clay soils (Bell 1993).

Various ranges of percentage of cement used have been cited in the literature (Tsonis et al. 1983; Nicholson, 1998) which typically falls within 5-30% by weight of the soil to be treated in order that consolidation of the soil-cement is insignificant. Feng et al. (2001) consider a range of 10 - 30% by dry weight of the soil a rather too conservative value for situations where small to moderate loads were applied. They observed that the addition of cement to soft mud made the soil behave as an over-consolidated clay and the cement-induced preconsolidation pressure was a function of cement content and curing time. In conclusion they recommend 6% cement content to soft mud was effective in developing the preconsolidation pressure, reducing the secondary compression index and increasing the coefficient of consolidation of the soft mud. Noting that the suitability of a clay soil for cement stabilization is dependent on its texture, and chemical and mineralogical composition (Bell, 1993), it may be necessary to establish these properties coupled with laboratory testing to determine the most appropriate proportion of cement required for any one particular case.

b) **Lime Stabilization**

This method of ground improvement has been long established for the treatment of expansive soils. Lime stabilisation has been carried out on a wide range of soils from clayey gravels through to clays, including some industrial waste materials such as fuel ash. ICI (1990) recommends soils with reactive clay content of over 10% as the most suitable and soils with Plasticity Index (I_P) above 10 as generally suitable for the application of this method. The Reactivity Index (RI) defined as the ratio of I_P to the silt/clay content of the soil should be greater than 0.5 for lime modification affects to be beneficial and greater than 0.75 for full stabilization subject to a minimum I_P of 18. Where organic matter is present, this could be detrimental to the use of the lime stabilization method. The total sulphate content of the soil (where applicable) should not exceed 1% (ICI, 1990).

The lime in the form of quick lime (CaO) [also hydrated lime [$Ca(OH)_2$] reacts quickly with water producing the moisturized lime $Ca(OH)_2$ and generates heat causing a volume increase according to the equation (Lopez-Lara et al. 2001)

$$CaO + H_xO \longrightarrow Ca(OH)_2 + 65.3kJ/mol \qquad (2.6)$$

The water utilized in this reaction (as well as that removed from the soil system through evaporation caused by temperature increase) brings about significant improvements in the soil workability due to dewatering (Boardman et al., 2001). The significant effects are the decrease in plasticity index and the agglomeration effects, shrinkage and swelling effects of the clay (Lopez-Lara et al. 1999; Akawwi & Al-Kharabsheh, 2000). Other effects on the geotechnical properties of fine-grained soils include:

a) Reduction in the soil moisture content as the moisture is absorbed.

b) Increase in the optimum moisture content.

c) Decrease in the soil density at the Proctor Optimum.

d) Increase in the California Bearing Capacity (CBR).

For the method to be applicable, very minimal percentage lime addition usually 1-2 % or less (Joshi et al., 1981) has been recommended to bring about full cementing reactions. Rogers et al. (1997) in a series of laboratory initial consumption of lime (ICL) tests on four British clays recommended the maximum amount of lime needed for the modification of clay soils as 3%. However, Consoli and Thome (2001), from similar tests on Brazilian soft clay with organic matter of about 3%, found that 11% of lime was required for full stabilization.

In situations where the cementing strength is not essential, smaller percentage lime is used to reduce the plasticity of the clay. The changes in the strength and plasticity has been attributed to ion exchange in the short term but in the long term Boardman et al. (2001) consider an additional benefit due to pozzolanic reaction. ICI (1990) has listed these further improvements of the following soil properties:

a) Further increase in CBR

b) Increase in unconfined compressive strength.

c) Increase in shear strength.

d) Increase in tensile strength.

e) Improved stability against swell and shrinkage.

f) Improved frost resistance.

As in cement stabilization, lime stabilization is accomplished by the Deep Mixing method.

Table 2.10 typically illustrates the improvement of some properties of a soft clay treated with lime by the "Chemico-pile method". The results show very remarkable change in the undrained shear strength of the soil.

Depth (m)	Before treatment				After treatment		
	w_n (%)	γ (Mg/m^3)	e	C_u (kN/m^2)	w_n (%)	e	C_u (kN/m^2)
5.5-6.1	122.2	1.34	3.34	12.0	163.0	3.39	78.7
7.0-7.3	88.3	1.47	2.39	15.0	86.4	2.31	52.1
10.0-10.8	98.3	1.42	2.75	19.0	79.1	2.09	56.2
14.0-14.3	85.6	1.49	2.28	24.5	76.1	2.06	59.8

Note: All symbols have their usual geotechnical engineering meanings.

Table 2.10: Improvements in Soft Clay Properties due to 'Chemico-Pile' Treatment (after Kitsugi & Azakami, 1982)

c) Miscellaneous Additives

The use of other additives for the improvement of soft clays has been reported in the literature. Muntohar (1999) has proved the use of mixes of lime and rice husk ash dramatically improved the engineering properties of soft clays. The rice husks ash possesses pozzolanic properties. Chemical analyses of the ash show a very high silica percentage of between 86.90 – 97.30% (Wen-Hwei, 1986). A bonded gel [Ca (SiO3)] results when the silica reacts with lime. Muntohar and Hantoro (2000) however contend that lime–rice husk stabilization becomes advantageous in situations of very high in situ moisture conditions.

Kimura et al. (2000) have also shown that solidified coal ash can also be used as a substitute for sand in sand compaction piles for improvement of soft ground. The strength, permeability and grain-size properties of the solidified coal ash qualify its usage in that perspective.

Electro-osmosis

Originally developed for dewatering fine-grained soils this method involves the passing of a direct current from anodes to cathodes installed in the soil at predetermined locations. The passage of current through the soil results in migration of water from the anode to the cathode where it is removed (Bell, 1993). The effects of this induced drainage process on fine-grained soils is a decrease in the water content consequently causing consolidation and increase the undrained shear strength of the soil (Pilot, 1981). Further, ion migration, electrolysis and chemical reactions occur leading to the formation of new irreversible compounds. In the process chemicals such as calcium chloride and sodium silicate may be introduced into the soil and this is said to enhance stability of the soil either by ionic replacement occurring in the clay mineral content or by cementitious material deposited in the pore space.

Electrode separations of between 3.6 – 4.95m and Potential of 30 –180V are reported in the literature. Potential gradients in excess of 0.5V/m for long-term applications (Bell, 1993) lead to energy losses in the form of considerable heating of the ground and should therefore be avoided.

Quite a few publications on the method appear in the literature (Pilot, 1981; Casagrande et al., 1981, Bo et al, 2001) suggesting the method is of very limited application and indeed is reported to have been used in situations where virtually all other methods were impossible to apply. It has been found most useful in situations where there is shortage of fill materials for preloading or danger of slope stability. It is more effective in low permeable soils than in high permeable soils. Bo et al. (2001) have shown that the degree of improvement is largely dependent upon the magnitude of the applied voltage based on tests carried out on Singapore clays. Table 2.11 illustrates improvement in the consolidation properties (compression index, C_c and coefficient of consolidation, C_v), preconsolidation pressure (P_c) and vertical permeability (k_v) of some Singapore marine clay due to electro-osmosis process. The results are quite consistent with the above statement.

Test No	Parameter							
	C_c		C_v (m^2/yr)		P'_c (kPa)		k_v (m/s)	
	Before	After	Before	After	Before	After	Before	After
1	0.77	0.22	0.44	1.26	180	400	8.35×10^{-10}	2.9×10^{-11}
2	0.77	0.17	0.44	2.34	180	500	8.35×10^{-10}	3.8×10^{-11}
3	0.73	0.63	1.26	0.51	120	237	1.96×10^{-11}	5.8×10^{-11}
4	0.73	0.32	1.26	0.65	120	355	1.96×10^{-11}	3.7×10^{-11}

Notes: Electric potential difference for tests 1, 2, 3 and 4 are respectively 6, 12, 2 and 4 volts.

Table 2.11: Improved Properties of Singapore Marine Clays (after Bo et al., 2001).

Soil Reinforcement

Soil reinforcement is a well-known technique for use in retaining structures and earthworks and several other construction works. For embankments, it has long been known that incorporating material with a tensile capacity into the base of the embankment improves stability (Bassett, 1991).

Several soil reinforcement materials have been used. In early times natural reed and hazel branches were used but these have been systematically replaced by high strength polymers. Any material of any size and shape qualify for use provided it possesses the necessary tensile strength and affords the necessary friction surface to prevent slippage and failure by pulling out (Bell, 1993). Such a material should also be corrosion resistant. The most frequently used reinforcements include metallic strips (usually galvanized steel, aluminium alloy) and polymeric geosynthetic materials. Arrangement may be in the form of grids or strips, the grid found to be most suitable due to its resistance to pullout than strips (Schlosser, 1990). Even though there are no limitations on the geometry of the materials, Bergado et al. (1991) in a comparison between pullout laboratory and field test results on steel geogrids showed higher resistance values for the field tests due mainly to length differences. Embedment length of field geogrids was greater.

Soil reinforcement results in a very strong composite material mainly due to combined effect of the reinforcement, which is strong in tension and the soil, which is strong in compression. The tension in the reinforcement is built up through interaction between the reinforcement and the soil in the form of friction or adhesion and bearing resistance (Bergado et al., 1991). The method may not be particularly suitable for soft clays and other fine grained soils (Vidal, 1969; Mckittrick, 1979) due to the poor adhesion between fill and reinforcement however, it is envisaged (Bell, 1993) reinforced fill of soft materials can be successfully used for structures like embankments.

A more promising approach is the use of geotextile. The use of geotextiles as reinforcement gained recognition in the late 1980s in geotechnics when it became necessary to construct embankments on very soft foundations. The first use of woven geotextile for reinforcement of an embankment construction on soft foundation however dates back to 1971 (Holtz, 1975; Holtz & Massarsch, 1976). Geotextile or geogrids have been found to significantly increase the safety factor, improve performance and reduce costs where they are used, as compared with more conventional methods (Holtz, 1990; Haeri et al, 2000) due to their satisfactory performance. They have relatively low stiffness compared to metals hence are more compatible with soil regarding deformation.

From a finite element analysis, Majes and Battelino (1985) showed how the use of geotextile membranes for a road embankment overlying a soft clayey layer restrained lateral displacement of the subsoil, favourably modified the displacement pattern thereby reducing maximum settlement and increased the bearing capacity of the subsoil. Increasing the number of reinforcement layers saw significant decrease in the settlement of a 4m-road embankment. Similar observations were made by Alenowicz & Dembicki (1991) on a reinforced soil system when a two-layer model of a temporary road cross-section was reinforced with geotextile. Increase in the spacing between the geotextile layers also increased the load carrying capacity of the models. There is however no standardization on the spacing of geotextiles, an issue that could significantly affect the quality of the improvement and cost.

A wide selection of geotextiles is available. The selection of the proper geotextile for a specific project must be based on the major function or functions that the geotextile is supposed to perform. The function may be for soil separation, reinforcement, filtration and drainage, control of erosion. Geotextiles are commonly used in highways for embankment construction. In order for the geotextile to function as a reinforcer the natural soil subgrade should have a California Bearing Ratio of 2.5 (an equivalent unconfined compressive strength of 69kPa) or less, Koerner (1985).

The use of geotextiles however has some short comings. Several factors may mitigate against their use. The Joint Departments of the Army and Air Force (1995) has indicated the following limitations:

- Geotextiles are made of polymers whose physical properties degrade on exposure to sunlight. (An indication they may be used with caution in certain climatic zones). Addition of carbon black reduces the rate of degradation.
- Polymer materials become brittle in very cold temperatures. (Their use in frigid zones may therefore be limited depending on type of facility).
- Polymers may react with the ground water depending on the chemical composition of the ground water. (Polyesters can degenerate in high pH environments whiles polyamides may perform poorly in low pH waters).
- Polymers gain water with age if water is present.

From the foregoing a thorough consideration of these factors need to be assessed in selecting a suitable or acceptable geotextile. Geographic location and climatic conditions of the project has significant influence in the selection of geotextile for any particular facility.

More recently the use of synthetic fibre has been reported (Phillip & Juran, 1995). Multiple threads of the fibre (0.1- 0.2% of the weight of natural soil) are mixed in place with the natural soil. Cohesion is obtained through friction between the threads and the soil grains. The method is suitable for steep slope embankment construction, anti-seismic and anti-vibration foundations and also for foundations on compressible soils such as soft clays.

Biotechnical stabilization is a natural reinforcement method, which combines the use of live vegetation with retaining structures and revetments. This approach is a cost-effective method for stabilizing slopes against erosion and shallow mass movement. The method relies on the integrated and complementary functioning of both the biological (living vegetation) and mechanical (concrete, wood, stone and geofabrics) components for improvement of the ground.

Ground Freezing

This is the artificial lowering of ground temperatures so as to convert in situ pore-water to ice. The ice acting as cement, binds together the adjacent soil particles to increase their combined strength and make them impervious thus creating an ice wall. Ground freezing is used as a temporary measure in the following construction works:

- Underpinning.
- Support for excavation.
- Inhibit ground water flow into an excavation.
- Slope stabilization.
- Temporary containment of toxic/hazardous waste contamination.

Ground freezing has been successfully applied in congested urban environments with limited right of way and headroom requirements, where conventional earth retaining systems are difficult to construct (Munfakh, 2003). The method has been particularly useful in shaft sinking (Auld, 1985; Klein, 1989) and tunnel construction. In Belgium the method has been successfully employed for the following projects.

- Construction of the Pre-Metro in Antwerp in conjunction with underpinning.
- Construction of tunnels and retaining walls in Brussels.
- Infilling and sealing of old coal mine shafts.

Other instances where the method has been successfully applied include the construction of a tunnel beneath the telecommunications facility in Vienna, Austria where the ground between the tunnels and the building's foundation was frozen to reduce potential settlements and minimize their impact on sensitive telecommunication installations and also the construction of a 4.5m diameter tunnel of the Heights Hilltop interceptor in Cleveland, Ohio, USA, through an embankment of an active rail line to provide redundant support for steel liner plates and ribs used for the excavation (Munfakh, 2003). For each of these operations, freezing was accomplished through horizontal freeze pipes.

Bell (1993) presents a precise treatment of the methods of ground freezing. The basic principle is to circulate a cooling medium such as liquid nitrogen, brine, carbon dioxide, etc, through a suitable pipe system, which cools the formation in which the pipe system is embedded and thus converts the in-situ pore water to ice. The ice so formed, bonds the adjacent soil particles together therefore forming an impermeable structure with improved characteristics such as increased strength, stability and reduced permeability.

While the primary concept of converting soil pore water to ice is relatively simple, its applications to remediation projects require the complex integration of the thermal, structural and hydraulic properties of the soil as well as the construction know-how and specialized equipment.

The feasibility of a ground freezing method depends on the following:

- Site geological conditions.
- Site groundwater conditions.
- Thermal properties of the soil.
- Water content of the soil.

The method works in all types of soil, however, the most suitable formation is one that is free draining and relatively free of silt and clay. Some clays and silts may exhibit frost heave due to ground freezing. Mettier (1985) indicates intermittent refrigeration could mitigate heaving. High permeability strata may have a negative impact on the freezing process in the same way as groundwater flow through permeable strata can retard or even prevent freezing. Generally groundwater velocities of less than 5mm/day do not have a significant impact on the freezing process. The thermal properties of the soil include the frozen and unfrozen conductivity, frozen and unfrozen specific heat and latent heat. Typical values of the thermal properties for sand and clay are presented in Table 2.12. In general however, coarse-grained soils and rock freeze faster than clays and silts. Since energy is required for the phase change from water to ice during the freezing process, more energy and longer time for freezing will be required in situations where the water content is high.

Parameter	w_n (%)	Unit	Clay value	Sand value
Unfrozen conductivity	25	BTU/ft. hr. °F	0.92	1.2
Frozen conductivity	25	BTU/ft. hr. °F	1.1	1.0
Unfrozen specific heat	25	BTU/ft^3. hr. °F	41.5	41.5
Frozen specific heat	25	BTU/ft^3. hr. °F	29.3	29.3
Latent heat	25	BTU/ft^3.	3600	3600

Table 2.12: Thermal Properties of Sand and Clay (after Sopko and Aluce, http://www.groundfreezing.com/artificial_ground_freezing.html , 23/10/2003).

Grouting Techniques

Bell (1993) describes grouting as the injection of suspensions, solutions and emulsions into pores in soils to improve their geotechnical characteristics. This technique has been in use as a ground improvement methodology for a century or so. The process has found wide use in the construction of tunnels, shafts and dams in order to reduce percolation or increase the mechanical stability of water-bearing soil or rock. The process is also suited for foundation retrofitting, subsidence and liquefaction mitigation, contaminant containments and barriers, offshore construction and many others. Examples of projects for which the method has been used include several large structures such as the Channel Tunnel, the Storebelt tunnel, the Normandy Bridge and the underground railway lines in London and Paris (Gouvenot, 1998).The primary aim of grouting is to improve the strength, permeability and stiffness of soil or rock formations. In particular, grouting cuts off water flow, thus rendering the soil or rock impermeable.

According to Bell (1993) two categories of grout are known namely: suspension or particulate grouts (Bingham fluids) and solution or non-particulate grouts (Newtonian fluids).

Particulate grouts consist of cement-water, clay-water or cement-clay-water mixes. Silicates, lignins, resins, acrylamides and urethanes (Karol, 1982; Chi and Yang, 1985) are the common classes of chemical grouts with the silicates being the most widely used.

The various injection grouting techniques used by grouting contractors for ground improvement/ground modification can be summarized as follows:

a) Permeation Grouting

Permeation grouting has mainly been used in the construction of soft-ground tunnels, primarily for the subway systems under major cities around the world (Welsh, 1998). In this method grout is injected into the soil at low pressure to fill the voids without significantly changing the soil's structure or volume. There are wide varieties of binders which are used with this grouting technique. The choice of the binder is dictated mainly by the permeability of the soil. Generally, water and cement mixtures are used where the coefficient of permeability is greater than 1×10^{-2} cm/sec. In situations where the permeabilities are as low as 1×10^{-6} cm/sec, then more expensive resin-based grouts are used. Soils with permeabilities less than 1×10^{-6} cm/sec are normally not groutable by permeation.

b) Compaction Grouting

Compaction grouting involves the injection of a highly viscous grout with high internal friction into a compactable soil. The grout acts as a radial, hydraulic jack and physically displaces the soil particles; thus achieving controlled densification.

c) Claquage

Grout is injected into the soil at a high pressure through a special valved tube, thereby hydrofacturing the soil. The resulting fissures are filled with the grout and the surrounding soil is modified to create a densified mass.

d) Jet Grouting

This is an *in-situ* mixing of soils with a stabilizer (usually neat cement grout). Jet grouting is a replacement mixing technology that uses a high-pressure jet of grout to erode and mix the soils in situ, creating a blended soil/grout matrix with improved engineering properties.

This system differs substantially from the other ground improvement or ground modification techniques as it breaks up the soil structure completely and performs deep soil mixing to create a homogeneous soil, which in turn solidifies. The jet grouting technique can be used regardless of soil, permeability, or grain size distribution. In theory, it is possible to improve most soils, from soft clays and silts to sands and gravels by jet grouting. Although it is possible to inject any binder, in practice, water-cement mixtures are normally used. Where impermeabilization of the soil is required, water-cement-bentonite mixtures are typically used.

Jet grouting is a versatile and effective technique which can be used across a wide range of ground conditions. It involves the in-situ mixing of soils with cement grout to form a predetermined strength/permeability matrix. The inclusions formed by this process may be used for structural support, or for the control of groundwater.

The strength and permeability of the columns can be controlled by the water/cement ratio and the addition of admixtures to the grout. The diameter of the columns is controlled by the rotation and lift speed of the drill tool.

Jet grouting has been used for various projects including groundwater control, underpinning, tunneling and excavation support.

2.6 Design Considerations

Different structures have different performance requirements. Design of ground improvement scheme depends largely on the application and type of facility so that for an efficient level of improvement, the following basic questions should come to mind.

- What type of facility is the improvement required?
- What depth of treatment is necessary? (Should treatment be extended to the entire depth of the soil layer and how cost effective is that?). For instance in

a seismic liquefaction mitigation the extension of improvement to cover the full layer of soft soil may not be essential for lightly – loaded structures.

- What is the tolerable settlement under normal service?
- To what extent should improvement cover (only the foot print of the facility?)
- Service time (What will be the life span of the facility or improvement technique? For example the pores of band drains are known to become clogged by fines with time).

2.7 Discussion

From the foregoing, there are various techniques that can be used for the improvement of problematic soils and in particular soft soil (soft clay for that matter) so as to make it suitable for citing a civil engineering structure on it. But the selection of a suitable ground modification method depends on the characteristics of the in-situ soil and the application. A preliminary evaluation needs to be carried out for any new structure or even an existing one in order to adopt any ground improvement programme. Project performance requirements for the intended facility such as the loading conditions (static, transient or dynamic) and allowable deformations have to be carefully assessed having in mind the effects of natural hazards such as earthquakes or floods.

Great variations exist in the conditions of the subsurface material even within narrow levels. An unqualified site characterization is therefore essential to give a clear view of the underlying lithology, the ground water conditions and the engineering properties of the soil. This will provide the necessary information that will aid making decisions on the appropriate ground improvement method for a particular facility. For most of the ground improvement methods cited above, the designs are based on empirical guidelines rather than any theoretical or rigorous design procedures. Extensive field testing programmes are therefore necessary to ascertain any final design.

The use of additives for ground improvement should call for knowledge of the clay mineralogy of the soil to avoid any over design but this will depend on other factors such as the moisture content of the soil and climatic conditions.

Throughout the literature quite wide ranges are given in the dimensions of some of the improvement structures such as stone columns, cement and lime columns and vertical drains, which again require implementation of field testing programmes. These dimensions control the extent and quality of ground improvement. A need for standardization of these dimensions is essential for cost effectiveness of the method of approach.

Significant variations in the ground conditions may also require some flexibility in the approach to ground improvement such that more than one technique is implemented in order to achieve better results. Most of the methods presented above can be used for the improvement of more than one soil type.

From the foregoing, it must be stated that a lot of experience is required to successfully implement any of the aforementioned ground improvement techniques and even those not covered in this thesis. This empirical nature makes ground improvement quite a suitable area for the application of knowledge-based systems technology.

2.8 Conclusion

Many ground improvement techniques are described in the literature. The above review only demonstrates the extent to which ground improvement technology has been used in solving many foundation problems that are encountered on problematic soil deposits. The facilities to which ground improvement methodology can be applied are numerous. The multiplicity of the methods that can be applied for the improvement of a particular soil makes the decision to select an appropriate method for a project a difficult task.

CHAPTER 3

DEVELOPMENTS IN PROBLEMATIC SOIL ENVIRONMENTS

3.1 Introduction

Even with numerous years of experience in construction on poor quality ground particularly soft ground in the Scandinavian countries, some Asian countries like Japan, Singapore and Thailand and elsewhere, the construction of civil engineering structures on these soils is still fraught with constant problems. This may be partly due to the complex nature of the structures under development. Having a good knowledge of the type of facility to be founded or constructed on the poor quality soil formation gives the geotechnical engineer a better direction of the type of geotechnical mechanisms on which to focus attention and subsequently the nature of any ground investigations and laboratory testing programmes to conduct.

Two important factors that dominate any foundation analysis therefore are the type of structure and site chosen for the development. The type of structure is indicative of the loading condition and settlement tolerances (West, 1976).

The chapter starts with a discussion on the types of civil engineering structures that are constructed on problematic soils in Section 3.2. The two types of structures that are common in the construction industry namely load imposed structures and load reduction structures are discussed.

The general geotechnical problems relating to stability, settlement and deformation that may be encountered during and after the construction of a facility in or on problematic soils are presented in Section 3.3.

Even though any type of structure may be sited on problematic soils, certain types of facilities have been found to be more prone to problems thus calling for more caution in their development on problem soils. Consequently a brief mention of the types of habitually troublesome structures is made in Section 3.4.

The choice of soil parameters that may need to be investigated in order to adequately design the proposed structure or even decide on the construction methodology is presented in Section 3.5. The parameters listed only serve as guide to the engineer.

The various types of construction options that the engineers use when faced with the development of a structure on problematic soils are briefly mentioned in Section 3.6. The most certain approach is to avoid the problematic soil deposit altogether by the use of piles, piers or caissons. However this method is a rather expensive venture and other alternative methods may be considered where applicable.

Section 3.7 presents the conclusions on the chapter.

3.2 Types of Civil Engineering Structures on Problematic Soils

Various types of structures (both earth and non-earth structures) may be constructed on/in problematic soils if steps are taken to improve the quality of these soils. The different situations in which ground treatment is implemented range from small housing developments to large civil engineering works (Charles, 2002) such as airport runways, bridges, quays and complex structures such as tunnels etc. The design of such structures, however, requires some consideration, primarily in terms of:

a) The nature and size of the structure, as a whole and its various components.
b) Surface environmental considerations, effects on neighbouring structures, utilities, traffic, etc.
c) The ground conditions for example, the subsurface material characteristics.
d) The groundwater situation.

There are two broad types of structures based on the loading condition. These can be classified as:

a) Structures that impose load on the subsoil.
b) Structures that remove load from the subsoil.

Figure 3.1 illustrates these broad classes with some typical examples.

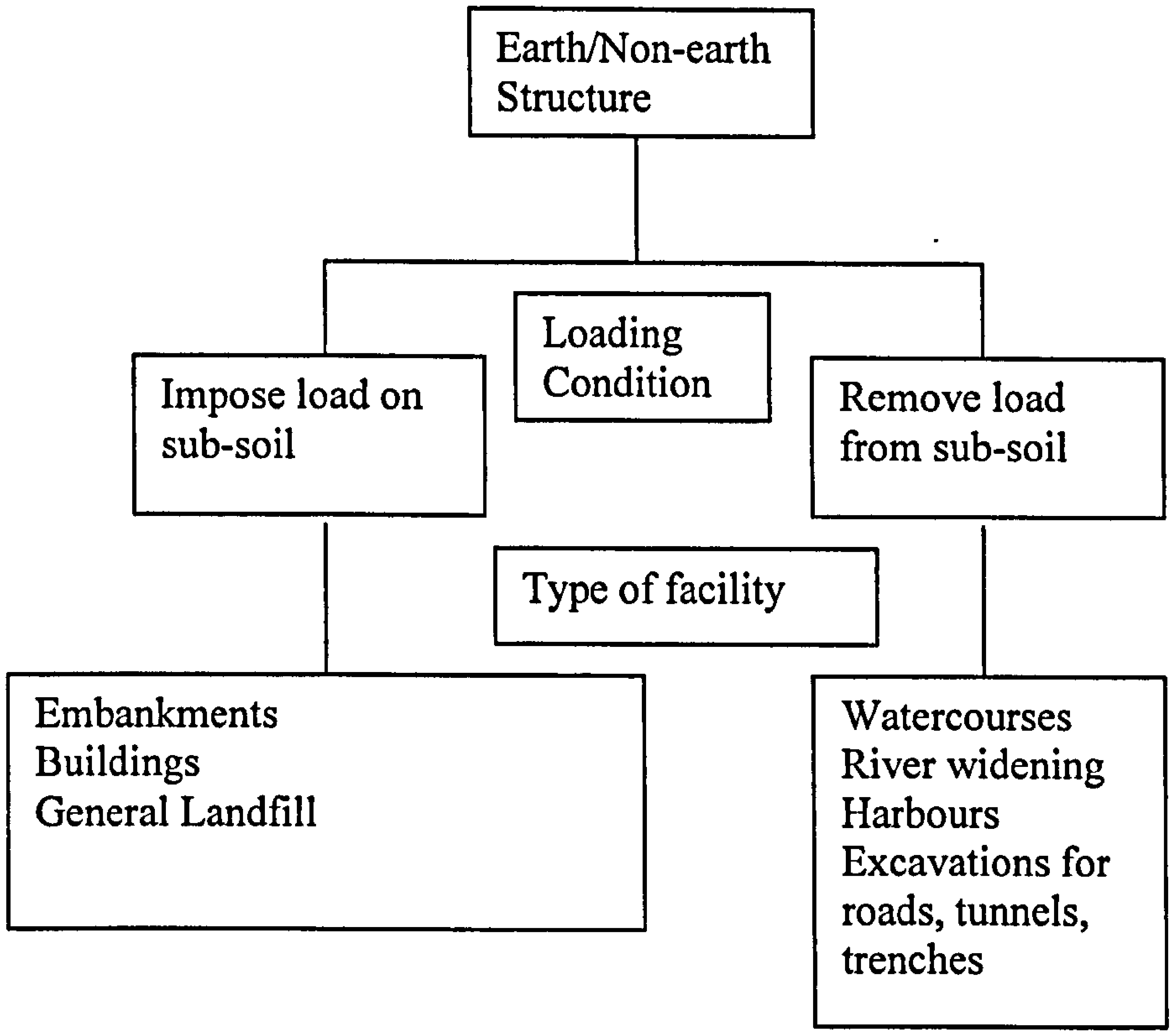

Figure 3.1: Classification of Civil Engineering Facilities Based on Loading Condition.

The Eurocode 7 classification of structures distinguishes 3 categories namely:

a) Geotechnical category 1 structures.

This category comprises of small and relatively simple structures. For such structures it is possible to ensure that the fundamental requirements for their development would be satisfied on the basis of experience and qualitative geotechnical investigations. There is also negligible risk for property and life. Examples of structures in this category are simple 1 and 2 storey houses with a maximum design column load of 250kN and 100kN/m for walls.

b) Geotechnical category 2 structures.

All conventional types of structures and foundations with no abnormal risks or unusual or exceptionally difficult ground or loading conditions fall under this group. Quantitative geotechnical data and analysis are required in their execution to ensure that the fundamental requirements be satisfied. Typical examples of structures in this category include spread foundations, embankments and earthworks and bridge piers and abutments.

c) Geotechnical category 3 structures.

The types of structures that fall into this category are very large and unusual structures, structures involving abnormal risks or unusual or exceptionally difficult ground or loading conditions and structures in highly seismic areas.

3.2.1 Load Imposed Structures

A great majority of civil engineering facilities impose load on the foundation soil. Table 3.1 shows some of the common types of structures in construction today. The list is by no means exhaustive and could be expanded to include the different types of facilities emerging today as a result of human development associated with issues such as security and transport.

Type of facility		
Embankment	Building	Land Fill
a) Road, motorway and railway networks • Linear embankments • Access embankments • Embankments across valleys b) Airports • Runways c) Hydraulic schemes • Dams • Retention dykes d) Irrigation and flood control works • Regular dams e) Harbour installations • Seawalls • Quays • Breakwaters	a) Residential/Office • High rise (>6 stories) • Medium rise (3-6 stories) • Low rise (<3 stories) b) Industrial • Heavy • Light c) Trading centres	General fill • Waste soil dump • Industrial waste • Domestic waste

Table 3.1: Typical Types of Load Imposed Facilities.

Structures that impose load on the subsoil cause stress build up in the soils that they are founded in. As an illustrated account, CUR (1996) has indicated that in the construction of embankments, the application of a load to highly compressible strata of low bearing capacity results in an increase in the water pressure of the layers as in the first instance the load is supported by the pore water. During this period, no significant changes occur in the effective stresses present in these layers and consequently the shear resistance also remains unaltered. Drainage of the excess water results in increase in the effective stresses and subsequently, the ground consolidates. Based on the thickness and low permeability of the compressible strata, this drainage process may take a long time to complete. The filling time during the construction stage is much shorter in practice than the time needed for the water to drain away and for the soil to consolidate. During the filling operations, therefore, shear stresses may occur at the edges of the fill which cannot accommodate the shearing resistance at that point. The excess water pressure ceases to increase as soon as the filling operations come to a halt and subsequently the soil consolidates there onwards.

3.2.2 Load Reduction Structures

These are mainly structures that are constructed on or in soils by excavation and removal of the in-situ soil thereby resulting in a reduction of load. In an excavation process, removal of load results in reduction in effective stresses in the subsoil thus making the soil less firm. In the first instance, there occurs a reduction in the water pressure, with the effective stress and/or shearing resistance remaining unaltered at all levels. Initially, the slopes and excavation bases remain stable, but with time the pore pressures rise resulting in the diminishing of the shear resistance of the layers. Typical examples of load reduction structures include, water courses, tunnels and general excavations for roads and rail line construction.

The characteristics of each of the above categories of structure signify the type of load density to be imposed by the structure, the required bearing pressure on the subsurface material so as to adequately support the structure and the tolerable settlement that such a structure could be subjected to for it to be of service. These parameters form the core of all analytical assessment for the successful implementation of every geotechnical development. Variations in the parameters may result from issues such as complexity of structure in relation to others such as risks to property and life. In situations where the structure to establish is uncomplicated, light or involving small earthworks, the basic procedure recommended by Eurocode 7 is to ensure that the fundamental requirements are satisfied on the basis of experience and qualitative geotechnical investigations. For instance, the required bearing pressures and allowable settlement for buildings will depend on whether a low-rise, medium-rise or high-rise structure is concerned or whether it is a trading centre, an industrial set up or an office/residential unit. The issue of experience on similar soils could be applied in the design of foundations for a low-rise residential building.

3.3 Geotechnical Problems on Problematic Soils

Some of the problems associated with the different types of poor soil formations are shown in Table 3.2. The aim of any geotechnical design procedure is therefore to eliminate or minimize the effects of these problems on the structure to be put in place.

Problem soil type	Characteristic	Problem
Weak and compressible soil	Low strength	Stability
	High compressibility	Large settlements Deformation of structure Prolonged construction timetables High cost of construction and repair over long periods of use
	Low permeability	Costly techniques of drainage
Expansive clays	High expansion potential	Large settlements Ground heave Deformation of structure
	High compressibility	Large settlements Deformation of structure Prolonged construction timetables High cost of construction and repair over long periods of use
	Low permeability	Costly techniques of drainage
Collapsible soils	Low density	Settlement due to collapse Deformation of structure
	High void ratio/porosity	Deformation of structure Mass movements
Liquefiable soil	High sensitivity	Deformation of structure Settlement of structure
	High permeability	Settlement of structure Deformation of structure
	Saturation	Costly techniques of drainage
Frozen soil	High degree of saturation	Deformation of structure Settlement
	High hydraulic conductivity	Ground heave
	High capillary action	Ground heave Deformation of structure
Peat and organic	High Compressibility	Large settlements Deformation of structure
	Low strength	Stability

Table 3.2: Summary of Problems Associated with Problematic Soil Type.

The problems are mainly related to:

a) Settlement/heave
b) Deformation and
c) Stability.

Therefore the performance criteria for structures on problematic soils must be in terms of the above. It is however important to state that the degree to which any of these becomes a problem is also dependent on the type of facility. For example, whereas settlement is a major problem on all compressible soils, its effects on the long profile of an airport runway, for instance, may be of much more concern in comparison to the same degree of settlement on long stretches of a road embankment. Any flaws in the level of the airport runway could result in very serious consequences in terms of safety of the passengers. In the case of differential settlement on the long stretches of a road embankment, vehicular travel on this stretch of the road could still be conducted with safety. Similarly, in situations where foundations are involved, differential settlement would have a more devastating effect to a high-rise building as compared to a single-storey building.

Given the wide variety of buildings and soil conditions on which they are founded, differential settlement could result in some of these structures exhibiting some tilting or warping effect. In situations where there are pronounced effects of these consequences, potentially damaging stresses may be imparted to the building's framework thereby reducing the performance level of such a building.

3.3.1 Foundation Settlements

Foundations are designed with the view of safely transmitting structural loads, which act primarily downwards into the ground. There are several kinds of foundations and the proper selection depends on the magnitude and direction of the structural loads and the subsurface conditions among others.

Two broad types of foundations are identified namely shallow foundations and deep foundations.

A shallow foundation is described as one whose depth below the surface (z) is equal to or less than its dimension, B. There are two major types of shallow foundations:

a) Spread footing which is described as an enlargement at the bottom of a column or a bearing wall that spreads the structural loads over a certain area of soil and
b) Mat foundation or raft foundation, which is a large spread footing that encompasses the entire structure. Mat foundations spread the weight of the structure across a large area and therefore reduce the induced stresses in the underlying soils.

The shallow foundation is by far the most common structural foundation in today's construction industry and used primarily for ordinary building. It has the following advantages:

a) Affordability in terms of cost.
b) Simple construction procedure.
c) Availability of materials (mostly concrete).
d) Does not require labour expertise.

The disadvantages of using this type of foundation result from settlement problems, irregular ground surface and the likelihood of the foundation being subjected to pullout, torsion and moments.

A deep foundation on the other hand is one whose depth below the surface is greater than its least dimension. Such a foundation transmits some or all of the structural loads to deeper soil or rock and is primarily used for major or larger structures or when the shallow soils are poor. Several types of deep foundation are known. They are classified into three broad categories as follows:

- Piles: described as poles made of steel, wood or concrete that are driven into the ground.
- Drilled piers, which are large diameter, concrete cylinders built in the ground. The construction of such a structure involves drilling a large diameter hole into the ground and subsequently filling the hole with concrete.
- Various hybrid methods.

Deep foundations are generally resorted to with the aim of bypassing the poor subsurface soil or when large structures are to be established. The use of such a method does not constitute a ground improvement methodology, and hence is not considered relevant to this study.

For a given loading system Koerner (1985) has stipulated three important areas of consideration as regards shallow foundations namely:

- Footing placement, which encompasses proper siting in terms of location and depth.
- Safety against bearing capacity failure, which involves an adequate footing design with regards to the strength of the foundation soil or rock.
- Tolerable foundation settlement involving estimates of the anticipated settlement in comparison to the allowable settlement that the structure will stand.

Causes of foundation settlements are two fold.

a) Settlement under load and
b) Settlement due to other causes.

a) Settlement under load

The types of settlement that should be considered in every shallow foundation footing design are:

a) Immediate settlement.
b) Consolidation settlement.
c) Secondary consolidation settlement.

These settlements are sequential and their occurrences are dependent on the type of soil under consideration. For any settlement analyses, the total settlement is given by the sum of all three components.

Immediate settlement

Immediate settlement or elastic settlement occurs during or immediately after the construction of the structure. It is estimated on the basis of the Terzaghi classical elasticity theory and is given by the following relation.

$$p = qB\frac{1-\mu^2}{E}I_w \tag{3.1}$$

Where p = settlement

q = contact pressure

B = characteristic length of the loaded area

E = modulus of elasticity of soil

μ = Poisson's ratio of soil (= 0.05 for saturated clays)

I_w = influence factor depending upon footing geometry and location

Equation 3.1 is generally applicable to granular soils at all moisture contents ranging from dry to saturated and for fine-grained soils at moisture contents less than 70%.

Consolidation settlement

This is associated with fine-grained silts and clays. Consolidation settlement occurs due to gradual expulsion of water from the voids of the soil resulting in a volume change that is time dependent.

Secondary consolidation settlement

Secondary consolidation settlement occurs after completion of primary consolidation. The process is insignificant for inorganic clays and silty clay soils.

b) Settlement due to other causes

Foundation settlement could also result from other causes such as:

a) Underground erosion of subsoil formations creating cavities which cause settlement when they collapse.
b) Structural collapse of some soils such as loess, saline, non-cohesive soils, gypsum silts and clays resulting from dissolution of soluble components that bind the soil grains.
c) Frost heave, which may occur when thaw occurs.
d) Mining subsidence which may occur as a result of collapse of voids created in the ground following mining operations.

Whatever the cause of settlement maybe, it is pertinent to take every suitable measure to reduce the settlement due to any of the above causes. The performance criteria for the proposed structure could therefore be in terms of total settlement, differential settlement, tilt or relative deflection (Wahls, 1994). Where there are large differential settlements between various parts of a structure, damage may occur due to additional moments that develop. Arora (1989) has found from several observations of various buildings that, in general, differential settlement is less than 50% of the maximum settlement and seldom exceeds 75%.

In order to control settlement and prevent the structure from damage due to settlement, allowable maximum settlements ranging from 20mm to 300mm have been generally permitted for various structures. As a guide to the designer therefore, various researchers have attempted to establish a number of allowable settlements for various structures. Examples of some of these attempts made by Sowers and Sowers (1970), and The Indian Standards Code IS 1904–1978, are presented in Tables 3.3 and 3.4 respectively for comparative purposes.

Type of movement	Limiting factor	Maximum allowable settlement
Total settlement	Drainage and access	15 to 60 cm
	Probability of differential settlement	
	• Masonry walls	2.5 to 5cm
	• Framed buildings	5 to 10cm
Tilting	Towers, stacks	0.004B* §
	Rolling of trucks, stacking of goods	0.01S* §
	Crane rails	0.003S* §
	Brick walls in buildings	0.0005S to 0.002S* §
Curvature	Reinforced concrete building frame	0.003S* §
	Steel building frame, continuous	0.002S* §
	Steel building frame, simple	0.005S* §

Table 3.3: Maximum Allowable Settlements Based on Type of Movement (after Sowers and Sowers 1970).

** B is base width: S is column spacing; § =Differential settlement in distance B or S*

Foundation Type	Sand and hard clay			Plastic clay		
	Maximum settlement (mm)	Differential settlement	Angular distortion	Maximum settlement (mm)	Differential settlement	Angular distortion
Isolated						
a) Steel structure	50	0.0033L	1/300	50	0.0033L	1/300
b)R.C.C	50	0.0015L	1/666	75	0.0015L	1/666
Raft						
a) Steel structure	75	0.0033L	1/300	100	0.0033L	1/300
b)R.C.C structures	75	0.002L	1/500	100	0.002L	1/500

Table 3.4: Maximum and Differential Settlements; IS: 1904–1978 (after Arora, 1989).

Note: L = spacing between two columns   R.C.C = Reinforced Concrete Column

Table 3.5 shows earlier attempts by Skempton and MacDonald (1956) and later Grant et al. (1974) to establish the allowable maximum settlement of various foundation types. A maximum settlement of around 25mm has been stated as a safe guide for buildings on isolated pad footings whereas buildings on rafts could tolerate greater total settlements (Padfield and Sharrock, 1983). For normal structures with isolated foundations, Eurocode 7 recommends total settlements of up to 50mm and differential settlements between adjacent columns of up to 20mm.

Foundation type	Maximum allowable settlement		
	Soil type	Skempton and MacDonald, 1956	Grant et al, 1974
Isolated footings or piles	Granular	600 $(p/s)_{max}$	$600(p/s)_{max}$
Isolated footings or piles	Fine-grained	$1000(p/s)_{max}$	$1200(p/s)_{max}$
Mat foundation	Granular	$750(p/s)_{max}$	$750(p/s)_{max}$
Mat foundation	Fine-grained	$1250(p/s)_{max}$	$1250(p/s)_{max}$

Notes: p = settlement *s = column spacing*

Table 3.5: Maximum Allowable Building Settlements for Various Foundation Types and Soil Conditions (adopted from Koerner, 1985).

Comparing the data in Tables 3.3, 3.4 and 3.5 there appears to be no unique acceptable maximum allowable settlements for the structures under consideration. The differences may result from the factors that have been taken into consideration during the establishment of these allowable settlements, for instance, the soil types. The Skempton and MacDonald (1956) and Grant et al. (1974) maximum allowable settlements presented above are based on broad soil types, (e.g. fine grained soil). Such a generalization does not take into account the significant differences in the behaviour of soils even with very minor differences in their properties. There however appears to be agreement in the values of the maximum differential settlement as presented above. The Indian standard code IS: 1904 – 1978 may pertain to practices in India based on local considerations.

Attempts have also been made to establish acceptable deflection limits for various structures (Table 3.6). For the same type of structure, different limiting angular distortions have been stated by the various researchers for structural damage. The values presented by Meyerhof (1947) and Polshin and Tokar (1957) appear to be more sensitive. An angular distortion of 1/500 has been recommended as the limiting value if cracking in walls and partitions is to be prevented in framed buildings and reinforced load bearing walls.

<table>
<tr><th rowspan="3">Type of structure</th><th rowspan="3">Type of damage</th><th colspan="4">Limiting values</th></tr>
<tr><th colspan="4">Values of relative rotation (angular distortion), β</th></tr>
<tr><th>Skempton and MacDonald (1956)</th><th>Meyerhof (1947)</th><th>Polshin and Tokar (1957)</th><th>Bjerrum (1963)</th></tr>
<tr><td rowspan="2">Framed buildings and reinforced load-bearing walls</td><td>Structural damage</td><td>1/150</td><td>1/250</td><td>1/200</td><td>1/150</td></tr>
<tr><td>Cracking in walls and partitions</td><td>1/300 (but 1/500 recommended)</td><td>1/500</td><td>1/500 (0.7/1000 to 1/1000 for end bays)</td><td>1/500</td></tr>
<tr><td colspan="2" rowspan="2"></td><td colspan="4">Values for deflection ratio Δ/L</td></tr>
<tr><td>Meyerhof (1947)</td><td colspan="2">Polshin and Tokar (1957)</td><td>Burland and Wroth (1975)</td></tr>
<tr><td rowspan="2">Unreinforced load-bearing walls</td><td>Cracking by sagging</td><td>0.4 x 10^{-3}</td><td colspan="2">L/H = 3:0.3 to 0.4 x 10^{-3}</td><td>At L/H = 1: 0.4 x 10^{-3}
At L/H = 5: 0.8 x 10^{-3}</td></tr>
<tr><td>Cracking by hogging</td><td>-</td><td colspan="2">-</td><td>At L/H = 1: 0.2 x 10^{-3}
At L/H = 5: 0.4 x 10^{-3}</td></tr>
</table>

Notes: L = Length of structure, B = Height of structure

Table 3.6: Limiting Values of Distortion and Deflection of Structure (after Tomlinson, 1980).

Acceptable deflection limits have also been established for various structural elements such as beams, cantilevers, and floors etc using quite diverse criteria (Table 3.7). These values as presented therefore serve as a guide to the designer in order to control or eliminate any undesirable deflections which may adversely affect the overall performance of the structure after construction.

Element	Criterion	Allowable deflection
Vertical deflections		
Beam	Steel beam total deflection	Span/200
	Reinforced concrete beam	Span/250 or 30mm
	Cracking of brick or blockwork partition*	Span/500 or 15mm
	Cracking of light weight partition	Span/350 to span/360 or 20mm
	Live load visible deflection #	Span/360
	Upward deflection because of precamber	
Floors or roofs	Differential settlement	Span/250 to span/500 depending on cladding
	Timber flooring	Span/330
	Paved or asphalt covering	Span/250
	Flexible short span roof sheeting	Span/125
	Movement of sensitive equipment (e.g. generator)	1 in 750 slope (for e.g.)
Cantilever	Visible deflection #	Span/180
	Cracking on cladding # (relative movement along edge)	Span/250 to span 500, depending on cladding
Gantry girder	Inefficient travel of overhead crane	Span/700
Lateral deflections		
Column	Sidesway of multi-storey building #	Height/1000 recommended
	Failure of frame with diagonals	1 in 600
	Racking of walls or infills of masonry structure	Height/500
	Single-storey or low-rise flexible frame	Height/300
	Visible deflection of canopy roof	Height/250
Mullions	Bending of support to glazing	Span/175
Gantry girder	Crane rail separation	Span/500

Table 3.7: Acceptable Deflection Limits for Structural Elements (after Alexander & Lawson, 1981).

Notes: All deflections are serviceability limits under worst total loading except

** Installation after depropping of floors   # Imposed short-term loading only.*

3.3.2 Stability Problems

Soil stability problems are generally encountered when slopes are concerned. This is particularly true when the poor soil formation has to be excavated for the location of facilities such as basements, the construction of slopes or where an embankment is involved. The contemporary methods of investigating slope stability are based on:

a) The assumption of a slip surface and a centre about which rotation takes place.

b) Studying the equilibrium of forces that act on this surface.

c) Repeating this process to find the worst slip surface.

The surface that yields the lowest factor of safety, F, is termed the worst slip surface. F is obtained from the following relation.

$$F = \frac{restraining\ moments}{disturbing\ moments} \tag{3.2}$$

F can also be obtained by dividing the soil strength parameters by partial factors based on Eurocode 7 recommendations. A soil is said to be stable if F is equal to 1 or greater. As a result 1 was taken as the minimum value of factor of safety for the stability of soil slopes.

3.2.3 Bearing Capacity Problems

Numerous attempts have been made to estimate the bearing capacity of foundation soils. The major parameters that are required to be determined are:

a) Ultimate bearing capacity defined as the average contact pressure between the foundation and the soil, which will produce shear failure.

b) Safe bearing capacity defined as the maximum value of contact pressure that a soil can be subjected to without the risk of shear failure. This parameter is based on the strength of the soil and computed by dividing the ultimate bearing capacity by a suitable factor of safety.

c) Allowable bearing capacity, which is the maximum allowable loading intensity on the soil allowing for both shear and settlement effects.

In the determination of the safe bearing capacity, the factor of safety, F, is usually taken as 3.0. High values of up to 5 may be used for very sensitive structures. Values of F lower than 3 are used for relatively unimportant structures.

Building codes in different countries suggest safe bearing capacity values that can be used for proportioning footings. Table 3.8 lists the safe bearing capacity (q_s) values reproduced from The British Standard BS 8004: 1986, while Table 3.9 gives a list of values from the New York Building Code and the Indian Standard IS: 1904 – 1978.

Significant differences exist in the values provided in these codes and this may indicate some variations in regional practices. Because there are no unified values in the standard codes, it may be necessary to rely on the prevailing accepted practice based on the location of the project to be undertaken. For instance, in the British Standard BS 8004: 1986 the safe bearing capacity for compact gravel, sand and gravel is 600-200 kN/m^2. For the same soil types, the safe bearing capacity is 440kN/m^2 in the IS 1904-1978 and 760-950kN/m^2 when considering the New York Building Code. In order to avoid any ambiguities, The British Standard BS 8004: 1986 has been adopted for the purpose of this work.

Type of rock/soil	q_s kN/m^2
Rocks (Values based on assumption that foundation is carried down to unweathered rock)	
Hard igneous and gneissic	10000
Hard sandstones and limestones	4000
Schicsts and slates	3000
Hard shale and mudstones, soft sandstone	2000
Soft shales and mudstones	1000-600
Hard chalk, soft limestone	600
Cohesionless soils	
(Values to be halved if soil submerged)	
Compact gravel, sand and gravel	>600
Medium dense gravel, or sand and gravel	600 – 200
Loose gravel or sand and gravel	<200
Compact sand	>300
Medium dense sand	300 – 100
Loose sand	<100
Cohesive soils	
(Susceptible to long term consolidation settlement)	
Very stiff boulder clays and hard clays	600 – 300
Stiff clays	300 – 150
Firm clays	150 – 75
Soft clays and silts	<75
Very soft clays and silts	Not applicable

Table 3.8: Presumed Safe Bearing Capacity, q_s, Values (based on BS 8004, 1986).

If site investigation results indicate that the safe bearing capacity of the foundation soil is below the expected value as indicated in the tables below, then there will be a requirement for improving this value before the structure can be built. The need for special foundation techniques such as ground improvement must be then addressed. If ground improvement is to be applied, the method to use should be one that must be capable of increasing the bearing capacity to the desired level in order to sustain the load from the intended structure.

Type of rock/soil	q_s kN/m^2	
	IS 1904-1978	New York Building Code
Rocks		
Hard sound rock	3240	1950 – 5800
Laminated rock	1620	760
Residual deposits of shattered and broken rock	880	110
Soft rock	440	760
Non-cohesive soil		
Compact gravel, sand and gravel	440	760 – 950
Compact and dry coarse sand	440	300 – 760
Compact and dry medium sand	245	-
Fine sand, silt	150	-
Loose gravel or sand	245	350
Loose and dry fine sand	100	90
Cohesive soils		
Hard or stiff clay, soft shale	440	480
Medium clay	245	190
Moist clay and sand clay mixture	150	-
Soft clay	100	95
Very soft clay	50	-

Table 3.9: Presumed Safe Bearing Capacity, q_s, Values (based on IS 1904-1978, and New York Building Code).

3.4 Habitually Troublesome Structures

Certain types of structures have been identified as the most troublesome particularly when located on problematic soil. Padfield and Sharrock (1983) have identified the following among others as the most typical:

a) Structures with a high proportion of imposed or cyclic loads such as silos and storage tanks.
b) Buildings with particularly brittle finishes or with the finishes applied early in the construction.
c) Furnaces, cold stores.
d) Sensitive equipment or machinery.
e) Pipework.
f) Marine structures.
g) Laterally loaded structures.

A preliminary knowledge about the type of structure focuses the engineer on what to pay more attention to during the preliminary assessment of the site. Buildings happen to be the most encountered structures in the construction industry. This makes it important to ensure that the foundation soil has or attains the necessary qualities before the structure can be erected on it.

3.5 Choice of Soil Parameters

Every site investigation programme is conducted with the aim of comprehensively identifying the ground conditions so that every analysis necessary for the successful implementation of the proposed project can be carried out. The economic and technical optimization of foundations for instance is only achievable as a function of the degree of confidence that the designer has of the assessment of the properties of the soils.

Generally, the nature of the proposed structure dictates:

a) The area of the site to be investigated.
b) The depth to which detailed information is required.

To obtain a better understanding of the nature of the underlying soil therefore a number of geotechnical mechanisms need to be thoroughly addressed. Table 3.10 shows some of the important mechanisms that need adequate attention in the site investigation process in relation to the type of structure. The two broad types of structures namely; load imposed structures (structure from fill) and load reduction structures (structure from excavation) are considered. From the table, the most common geotechnical mechanisms that apply to both types of structures are shearing, settlement and horizontal deformation. Some mechanisms are however considered more important depending on the type of facility. For example, whiles uplift is considered a major problem in the construction of a dam, in the case of a road excavation the issue of horizontal deformation should be better addressed.

Having these mechanisms in mind, the site investigation and laboratory testing programmes are then designed to obtain the relevant data for further analysis. The choice of soil parameters to investigate when considering the establishment of a building excavation for instance, should be geared towards obtaining parameters on shear strength, compressibility, bearing capacity and in particular squeezing. Such an approach, apart from being cost effective, also saves time in the investigation process.

Mechanism	Structure from fill				Structure in excavation			
	Dam	Roads & railway beds	fill[1]	Soil & other dump	Ditch, port, etc	Road & railway cutting	Building excavat-ion	Trench
Shearing	x	x	-	x	x	x	x	x
Uplift	(x)	-	-	-	x	x	x	x
Squeezing	x	x	-	x	-	-	(x)	-
Settlement	x	x	x	x	(x)	x	x	x
Horizontal deformation	x	x	-	x	(x)	(x)	x	x
Negative skin friction	x	x	x	x		-	-	-

Table 3.10: Earth Structures and Geotechnical Mechanisms (after CUR., 1996).

Notes; x: Mechanism of importance for the design. (x): Mechanism of possible importance for the design. - : Mechanism of no importance for the design. 1: applies to the middle extensive fills; for the edges, refer to the column on road and railway beds.

3.6 Construction Options

As noted in Section 3.2, the problems encountered in construction in poor soil environments are failure, settlement/heave and ground movements. The problem of settlement is often associated with structures such as buildings, dams, and embankments where as ground movements and failure are often encountered with slopes and excavations in general. In the past the basic construction options for these soils were:

a) Avoidance

In this approach, the inferior quality soil layers are relieved of the bearing loads. The structural load is transferred to a more competent layer at greater depth by the use of piles, caissons or piers. This is an expensive venture and may not be applicable in built up environments due to the installation methods but has the advantage of a high degree of certainty.

b) Partial or complete removal.

Here the poor quality material is either completely or partly excavated. The excavated material is then replaced with superior quality material. This may be applicable where the depth of the poor quality soil layer may be down to 3m. The advantage of this method is certainty but has the draw backs of been costly depending on the depth of excavation and volume of material to be excavated. It has the added disadvantage of creating environmental problems regarding the disposal of the waste material, contamination of surface waters and dust where very dry conditions exist. Where use can be made of the large volumes of the waste material, the method may be found suitable for the project.

c) Displacement

This method is particularly suitable to soft soil formations. It is a traditional method of embankment construction (CUR, 1996). In this method the low bearing capacity soil is forcibly displaced with sand to the side above ground level where it is excavated. The height of the embankment is quickly increased for the foundation material bearing capacity to approach that of an existing embankment of the underlying soft soil. Nagaraj and Muira (2001) indicate that the bearing capacity could then be exceeded by blasting the side of the embankment. Where thickness of the substratum is between 5 and 6m they recommend displacing the soft material by loading to cause failure. Soft clay strata with depths up to 15m have been successfully treated by this method.

The disadvantages associated with the method include the possibility of inclusions of low bearing capacity material occurring in the sections formed, the occurrence of soil heave dozens of meters outside the fill area thus making the method unsuitable for use in developed sites and the problem of disposal of heaved soil.

d) Load reduction

Load on the poor quality soil stratum material could be minimized by the use of lightweight materials as a means of improving stability and settlement reduction. Popovics (1978) and Schwab & Pregl (1978) have shown the possibility of the use of slag and fuel ash as embankment materials.

e) Improvement

In which the properties of the sub surface soil are altered in order to obtain better quality. This approach has been found to be more advantageous in terms of the total cost of the project as compared to other methods such as bypassing the poor quality material by the use of piles. The major disadvantage with the improvement option lies in the fact that there are a lot of uncertainties associated with the various methods of ground improvement that are in current use.

It is noted from Chapter 2 that various facilities have been established on poor soil formations in various parts of the world by improving or modifying the properties of these soils. Even though buildings are the most common types of facilities, the list is endless incorporating all types of load imposing structures to those that relieve the ground of load such as excavations. The type of facility determines the loading condition either as light, moderate or heavy or dynamic or static loads. The problems that may be encountered during and after establishing the structure irrespective of the loading condition have already been stated in Section 2.2 and later described in Section 3.3. For the improvement of settlement properties of the soil in order to avoid the various types of settlement ground improvement methodologies such as preloading, the vibro methods, vacuum consolidation and the stabilization methods can be applied.

The densification methods including dynamic compaction, surface compaction, blasting, vibrocompaction and compaction grouting, to mention a few, are used for the solution of bearing capacity and settlement problems depending on the type of material under consideration.

Stability problems can also be addressed by means of the aforementioned techniques and others such as the biotechnical and grouting methods.

3.7 Conclusion

A considerable number of civil engineering structures can be sited on poor soil formations. The major types of structures are buildings and embankments which impose load on the foundation soils. Other types of structures include watercourses, tunnels and excavations for roads and rail lines. These however result in the reduction of load on the subsurface soils.

The problems encountered on poor soil formations mainly centre on settlement, deformation and stability. Several design procedures to control settlement and deformation have been established to guide the geotechnical engineer in the analyses to either avoid or minimize these problems. For adequate performance of a structure on the poor quality soil the relevant geotechnical mechanisms however, need to be addressed. Elaborate site investigation programmes can then be designed to obtain the relevant soil parameters for any further design.

Whereas the properties of the soil may pose a problem for the structure to be placed, there are certain types of structures that have been found to be more problematic when founded on poor soil formations. The sensitivity of the structure or the nature of the load it imposes on the subsoil may be contributory factors.

In order to address the problem of construction on poor quality materials, a number of construction techniques have been used in both past and the present. These techniques include avoidance, partial or complete removal and displacement of the poor quality material and also improvement of the qualities of the materials.

CHAPTER 4

GENERAL INFORMATION ON KNOWLEDGE-BASED SYSTEMS IN GEOTECHNICAL ENGINEERING

4.1 Introduction

The concept of Knowledge-based Systems emanated from Artificial Intelligence in the mid. seventies when the need for special-purpose computer programs was realized with the view to adapt, learn, invent and accumulate the combined wisdom of a profession. Knowledge-based systems are computer programmes that are expert in some narrow problem area. These systems accumulate and codify knowledge that the computer may apply when type problems are encountered. Knowledge-based system or expert system organization is such that the domain knowledge (knowledge base) is separated from the system's general problem solving knowledge termed the inference machine.

The concept in its early stages in civil engineering (early 80s) suffered many pitfalls (Young and Hadgraft, 1989) due to the uncontrolled excitement it initially brought into the civil engineering community. Its application in civil engineering is now widening, covering an extensive range from analysis to design and knowledge acquisition.

The nature and complexity of the ground on which geotechnical practices take place more than qualifies geotechnical engineering for the use of knowledge-based systems technology. Indeed, geotechnical engineering is a field where qualitative and experienced-based knowledge has no substitute. Modern day trends of development, the remote locations of projects and safety of structures call for the development of working knowledge-based systems to provide an efficient user-friendly environment for the geotechnical community and in particular to assist young inexperienced geotechnical practitioners. This in a way is a very subtle manner of knowledge sharing thus preserving it. However, expert system or knowledge-based system technology is still in the developmental stages in geotechnical engineering, having been used in the geotechnical engineering field for only a decade and half. Even in this youthful stage several attempts have been made to develop expert systems for the geotechnical engineering field. To date the majority of existing knowledge-based systems in geotechnical engineering unfortunately, are either prototypes or are still research based.

An attempt is made to bring to light how far the technology has been assimilated in the geotechnical engineering community and the extent to which the technology can be used for the improvement of problematic soils for construction purposes.

4.2 What Knowledge-Based Systems are

A knowledge-based system is described as a computer program, which emulates the behaviour of a human expert within a well-defined, narrow domain of knowledge. The knowledge is obtained from human domain experts who provide the necessary knowledge of the problem domain through their problem–solving methods, strategies and rules of thumb for problem solving. Knowledge so acquired is coded into a form that the computer may apply under similar conditions (Waterman, 1986, Luger and Stubblefield, 1999). In effect therefore, knowledge-based systems have their roots in artificial intelligence (AI) and they are attempts to understand and initiate human knowledge in computer systems (Wiig, 1994). Knowledge-based systems are regarded as been synonymous to expert systems in some literature. Graham-Jones and Mellor (1995) however regard expert systems as a subset of knowledge-based systems (Figure 4.1). They distinguish between them on the following basis even though they all use rule-of-thumb knowledge.

- The problem solving technique used in expert systems involves moving from known items of information or seen concepts to unknown information or unseen concepts by making inferences on the known knowledge.

- Expert systems make use of more algorithmic and statistical approaches of knowledge representation compared to the symbolic approach of knowledge-based systems.

Knowledge-based systems or expert systems application is most suited under conditions of uncertainty and incomplete knowledge.

4.2.1 Components of a Knowledge-Based System

Knowledge-based systems consist of the following distinct components:

- The knowledge base – which contains a collection of facts and rules on the specific subject or domain.

- An inference mechanism – which contains the general problem solving knowledge.
- The human interface – which is used to enter and elicit information.

There are three types of people namely the expert, the knowledge engineer and the end-user (Edwards, 1991) who are mostly involved with building and using the system.

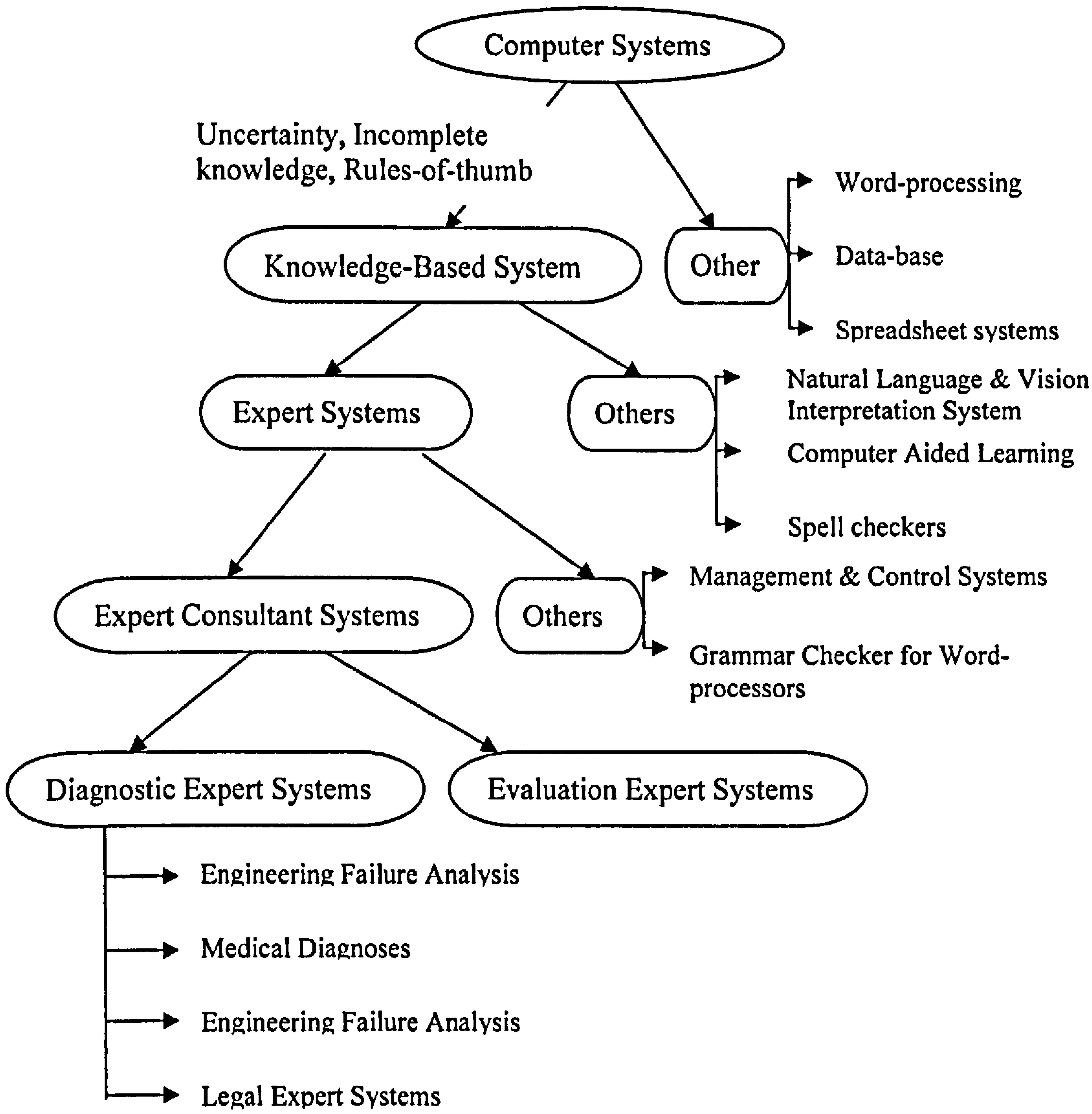

Figure.4.1: Computer Applications Schematic (modified after Graham-Jones & Mellor, 1995).

4.2.2 Significance of Knowledge-Based Systems

According to Liebowitz (1995), the significance of expert systems in industry stems from the following:

- They provide mechanism for building institutional memory in which case the loss of an expert does not erode his knowledge once this knowledge is preserved or documented in the expert system.
- They are a useful "substitute" for expertise deficiency.
- Availability is undoubted.
- Facilitate training.
- Improve productivity.
- Serve as a tool to help supplement the decision-maker.

These advantages which are applicable to geotechnical engineering by no means make expert system technology a panacea to geotechnical engineering problem solution. They exhibit a number of short falls among which Luger and Stubblefield (1999) identified the under listed;

- Difficulty in capturing the 'deep' knowledge of the problem domain.
- Lack of robustness and flexibility.
- Inability to provide deep explanations.
- Difficulties in verification.
- Little learning from experience.

These notwithstanding, the application of expert or knowledge-based systems technology to real world problem solution will continue to grow in engineering, scientific, military and medical applications and all aspects of human existence as our knowledge of the universe continues to unveil through technological advancement.

4.3 Knowledge Elicitation

Civil engineering structures founded on soil can fail to perform satisfactorily for numerous reasons among which include failure of soil and the structure itself. Therefore care must be exercised in representing knowledge for design for a knowledge-based system because the success of any design using the knowledge-based system depends to a large extent on the input knowledge.

Knowledge elicitation ranks among the most important but also the most difficult task in the development of a knowledge-based system. For an expert or knowledge-based system to have any use, the knowledge engineer should select appropriate building tools in addition to assisting the domain expert articulate the requisite knowledge. The knowledge so acquired should be implemented in a correct and efficient knowledge base that will be beneficial to the end user (Luger and Stubblefield, 1999). To this careful criteria must be adopted for knowledge elicitation.

Two classes of knowledge elicitation techniques described by Chung and Kumar (1987) are:

a) Psychological technique, which calls for Knowledge Engineer (KE) and Domain Expert (DE) interaction.
b) Machine induction where the computer automatically induces rules from examples.

Generally the first class may be more suited for geotechnical engineering due to:

a) Spatial variability of the ground on which geotechnical engineering is practised
b) Insufficiency of examples needed to construct a comprehensive encapsulation of expertise in any geotechnical domain, noting however that earlier research (Hart, 1985, Trimble et al 1986) has indicated no single elicitation method is proven to be universally effective.

This approach was therefore adopted for the purpose of this work.

The basic model for knowledge engineering has been that the knowledge engineer mediates between the expert and knowledge base, eliciting knowledge from the expert, encoding it for the knowledge base and refining it in collaboration with the expert to achieve acceptable performance. This basic model is represented by Gaines and Shaw, (http://ksi.cpsc.ucalgary.ca/articles/KBS/KSS0) with manual acquisition of knowledge from an expert followed by interactive application of the knowledge with multiple clients through an expert system shell (Figure 4.2). The procedure may be itemized as follows:

- The knowledge engineer interviews the expert to elicit his or her knowledge;
- The knowledge engineer encodes the elicited knowledge for the knowledge base;
- The shell uses the knowledge base to make inferences about particular cases specified by clients;
- The clients use the shell's inferences to obtain advice about particular cases.

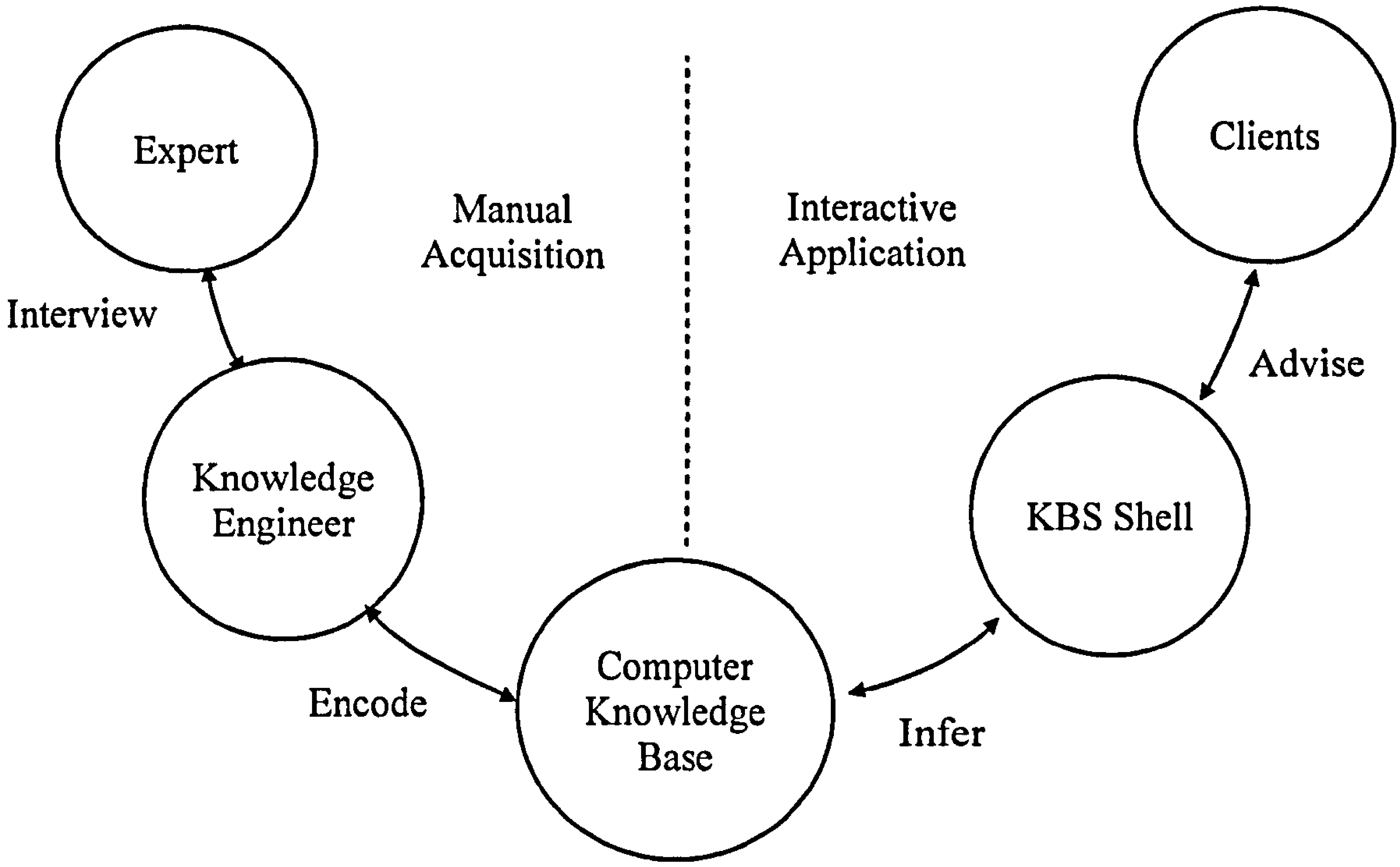

Figure 4.2: Basic Knolwedge Engineering (after Gaines & Shaw, https://ksi.cpsc.ucalgary.ca/articles/KBS/KSS0/)

4.4 Knowledge Representation

Knowledge representation in existing knowledge-based systems has taken the form of declarative knowledge and procedural knowledge. Declarative knowledge representation is a statement of facts without permission for explanation while procedural knowledge representation provides a way of applying the declarative knowledge. Declarative knowledge representation schemes include semantic networks, frames and production rules. Procedural knowledge is represented as production rules and scripts. Following are brief descriptions of these methods.

4.4.1 Rule-based Knowledge Representation

Rule-based knowledge representation falls among the most commonly used techniques for expert system development. Rules are used to represent heuristics or "rules of thumb", which specify.a set of actions to be performed for a given situation. Generally, rules consist of an *if* portion and a *then* portion. (IF a set of propositions is true, THEN some consequences follow). The *if* portion of a rule is a series of patterns that specify the facts (or data) which necessitates the applicability of the rule. The *then* portion of the rule represents the set of actions that are to take place when the rule is applicable.

Rules facilitate creation, modification and maintenance of the knowledge base because the knowledge is modularized. The continuous updating of domain knowledge with time calls for the addition of new rules and removal or modification of old rules in order to keep the knowledge base current. Rule-based knowledge representation permits easy editing of the rules.

4.4.2 Semantic Networks

In semantic networks, graphical representation of knowledge that shows the relationship between objects is used. They have been found to be an excellent way of representing declarative knowledge particularly when it has a hierarchical form. Semantic nets consist of *nodes* connected by links, termed *arcs* that describe the relations between the nodes (Waterman, 1986). The nodes represent objects, concepts or events. Some nodes may inherit properties or characteristics from other nodes. Nodes lower in the hierarchy can inherit properties from those higher in the hierarchy.

4.4.3 Knowledge Representation by Frames

A frame is a network of nodes and relations organized in a hierarchy, where the topmost nodes stand for general concepts and the lower nodes more specific instances of those concepts. A frame is divided into slots, which contain attributes of the object under reference. Frames are generally used to represent "stereotyped knowledge".

4.5 Knowledge-based Systems in Geotechnical Engineering

Great strides have been made in the last two decades or so since the inception of the concept of knowledge based systems in geotechnical engineering in the mid-80s. A review of knowledge-based systems by Moula et al (1995) demonstrates the extent to which the concept had been emulated in the field of geotechnical engineering in just under a decade of its realization. The paper focused mainly on soil engineering applications and attempts made to categorize the existing systems based on the domain field.

Toll (1996a) updated the review including rock engineering applications, neural networks, mining and geotextiles. The paper illustrates a much wider scope of coverage within the short span of time between its publication and that of Moula et al (1995). In short, apart from demonstrating the suitability of geotechnical engineering for the development of expert systems, it also portrays how fast the concept is growing in the geotechnical community. The review even though similar to Moula et al (1995) includes conventional knowledge-based systems, neural networks and integration of knowledge-based systems and other technologies such as Geographic Information Systems (GIS) and aerial and space imagery. Regrettably however, none of the numerous cited expert systems was in the operative stage. They were all still prototypes.

As the quest for geotechnical problem solution widens new developments have taken place since 1995. This section looks at the state of the art of knowledge-based systems technology in geotechnical engineering. The database for this work is based on published literature on geotechnical engineering knowledge-based systems.

4.5.1 Geotechnical Site Characterization

Conventional Knowledge-based Systems

Geotechnical site characterization is a primary requirement for any successful geotechnical engineering problem solution. The engineer must have some basic guidelines to conceptualize the nature and structure of the subsurface to aid in the design and safety of the proposed structure. These guide lines are the properties and the conditions of the subsurface material, which by every aspect show remarkable spatial variability.

The site characterization process involves preliminary to detailed site investigation together with extensive testing and monitoring to provide the engineer with the requisite knowledge to evaluate the soil profile, groundwater regime and soil properties. Safety of the proposed project depends largely on the manner of interpretation and use of the data obtained but more particularly the methods of acquisition of data. These steps, together with the method of description, or representation of geologic material are sources of uncertainty (Huang and Siller, 1997) in addition to uncertainty due to spatial variability (Christian et al 1994, Lacasse & Nadim, 1996). Spatial variations of soil properties may result from natural soil formation processes, the palaeo-stress state and other geologic processes in the history of the soil. Added to these, laboratory test results differ significantly from the in situ situation due to measurement biases (Chuang, 1995). A lot of engineering judgement is therefore required in the use of the data obtained. The level of appropriate judgement can only be obtained from experienced professionals.

Not unexpectedly therefore, a good proportion of the prototype knowledge-based systems were developed within the site characterization general domain. Over 30% of the number of knowledge-based systems cited in Moula et al (1995), Toll (1996a), Toll (1996b) was for ground characterization. This figure has significantly shot up in the last few years.

In the field of site characterization, typical examples of the early knowledge-based systems include SITECHAR (Rehak et al, 1985), CONE (Mullarky, 1986; Mullarky & Fenves, 1986), SOILCON (Wharry and Ashley, 1986, Siller, 1987), SITECLAS (Wong et al., 1989). These systems were developed to either advise on site investigation programmes, interpret geotechnical data or for classification purposes.

Borehole information has been used to develop knowledge-based systems (Lok, 1987; Adams et al, 1989; Toll et al 1992; Vaptismas and Toll, 1993 and Toll, 1994) for correlating soil layers creating ground profiles. The selection of field testing method plays a very significant role in the type and quality of data generated. Moula and Toll (1993) developed a knowledge-based system that gives advice on the type of geotechnical field tests to be used to obtain particular geotechnical parameters and the suitable ground types for applicability of the methods.

Davey-Wilson & Mistry (1995) developed a knowledge base system GeoPredictor that uses case-based reasoning techniques to predict geotechnical properties.

SIGMA (Oliver and Toll, 1995; Toll, 1995); ASSIST (Oliphant et al, 1996) are later developments that can be used to portray a graphic representation of the ground conditions.

Theory governing the behaviour of unsaturated soil shows that the soil-water characteristic curve is the central relationship that describes the behaviour of soil as it desaturates. Many soil properties such as hydraulic conductivity, shear strength, chemical diffusivity, specific heat etc can all be related to the soil-water characteristic curve. Fredlund et al (1996) have used knowledge-based systems technology to predict 10 different soil property functions to the soil-water characteristic curve. The system allows for the estimation of unsaturated soil properties when experimental data is limited or too costly to obtain.

Toll and Giolas (1998) developed a knowledge-based system for the estimation of soil and rock properties with the aim of providing geotechnical engineers a support tool for evaluating geotechnical properties. This was followed by the development of a correlations knowledge-base system (Giolas and Toll, 1999) which uses generic forms for the representation of correlations and minimizes any unqualified correlation inapplicable to the material in question. It could be described as a 'low cost' (cheap) quick means for ground properties estimation. Both systems use object hierarchies. The objected-oriented approach has been demonstrated to provide, to a large extent, flexibility and is amenable to future editing as compared to earlier knowledge-based systems, (e.g. Gillete, 1991 and Davey-Wilson, 1991). The usefulness of knowledge-based systems for geotechnical properties correlation lies in the fact that adequate information about the ground condition can still be made in situations where equipment is unavailable and eventually help keep down the cost of investigations.

"Soft Computing" Approach

a) Fuzzy logic

Fuzzy logic has now become a popular tool for solving geotechnical problems. It has been employed to effectively find solutions for a variety of problems such as site characterization, retaining wall selection, foundation analyses etc.

The concept gained recognition due to the imprecise, vague and ambiguous nature of the world. Successes in fuzzy logic and fuzzy sets applications have been because fuzzy theory reflects the true situation of the world where human thinking is dominated by approximate reasoning logic (Yang and Soh, 2000). Often various systems (ground in particular), exhibit characteristics that are too complex to be described with "pure" mathematical equations or models. In fuzzy logic the precise value of a variable can be replaced by an intuitive natural language the meaning of which is represented by a fuzzy set and inferencing carried out based on the representation (Pham and Pham 1999, Yang and Soh, 2000). In the fuzzy set theory (Zadeh, 1965), full membership is represented by a grade equal to 1 while a null grade of membership signifies complete exclusion.

Fuzzy logic technology is well known for its capability for rule–based expert system development. Such systems use compositional rule of inference as the knowledge they contain is expressed as qualitative statements. Huang and Siller (1997) used the technology for geotechnical site characterization by using both grain size characteristics and plasticity where the inclusion of plasticity to the fuzzy set more explicitly distinguishes the different soil types. A wider variety of soils can therefore be represented.

b) Neural Network Approach

Neural network methods are gaining fast recognition in geotechnology that their applications in geotechnical engineering now covers wide ground. Earlier applications in geotechnical engineering date back to 1991 when Zhang et al described an early application of a neural network to the evaluation of coal mine support.

Neural networks shift the emphasis of artificial intelligence away from problems of symbolic representation and sound inference strategies to problems of learning and adaptation (Luger and Stubblefield, 1999). Goh (1999) describe the methods as very simplistic mathematical representations of the biological learning processes of the human brain. An important characteristic of neural networks is their adaptive nature where "learning by examples" replaces "programming" in solving variables. The basic unit of the neural network is the neuron. These are arranged in layers. A neuronet typically consists of three layers. The input variables comprise the input layer to the network and the output layer contains the target output vector. In-between the input and output layers are hidden layers which assist the neural network in the learning process. The nodes in one layer are connected to all nodes in the preceding and following layers. Of the several neuronets that have been developed the three-layered feed-forward error-backpropagating network with supervised learning has been most used in many application fields of science and engineering (Najjar et al, 1996).

Neural networks have been used in predicting the characteristic properties of soils (Agrawal et al., 1994; Zhu et al., 1996; Zhu et al., 1998; Penumadu and Zhao, 2000). An Artificial Neural Networks (ANN) and Geographic Information Systems (GIS) approach was used by Gangopadhyay et al. (1999) for subsurface characterization. The artificial neural network was used as an interpolating tool for mapping the subsurface formation using the error back-propagation algorithm while the GIS was used for the development of the subsurface profiles based on generated data from the ANN. Though the system was developed for aquifer location it demonstrates how ANN and GIS could be used for ground profiling.

Interpretation of laboratory test data has been conducted by Goh (1999) by means of Generalized Regression Neural Network. The method demonstrates how c_v values could be obtained using neural network pattern matching capabilities based on Sridharan et al's procedure of determining c_v. In addition the method has also been used to classify soils based on the particle size distribution. Swelling potential of soils have also been accurately predicted by use of neural networks (Najjar, et al, 1999).

In order to alleviate the inaccuracies in the predictions of ground movements during tunnel driving Kim et al. (1999) developed NESASS (Neural network Expert System for Adjacent Structure Safety) an expert system that could reliably predict the ground movements including any damage to adjacent structures resulting from the tunnel excavation. The essence of the artificial neural network technique was to cater for both measured field data and tunnel construction information that are excluded from the learning process.

4.5.2 Slope Analysis

Conventional Knowledge-based Systems

Failures of slopes (natural or artificial soil or rock slopes) have very devastating consequences that may lead to considerable loss of life and property that care must be taken in their protection and the design of artificial ones. Safe and economic design and monitoring can be achieved if the geotechnical engineer has a thorough knowledge of the methods for checking the stability of slopes and their limitations. To aid in the design or stability analysis a number of knowledge-based systems have been developed to achieve this feat.

Faure et al, (1991), Mascarelli et al, (1992), Faure et al, (1995), developed XPENT a knowledge-based system for slope stability analysis. It was initially developed as a teaching aid but upgraded to be of use to the geotechnical engineer. Depending on the slope angle, cut slopes on competent or incompetent material may require considerable protection for safety. Several slope-protection structures are known and these are applicable to specific situations for example protection from falling stone. Hirokane et al (1993) describe a knowledge-based system to assist the engineer in the selection of the most stable, aesthetic and workable protection structure.

Wislocki and Bentley (1989) describe an expert system for the determination of planning applications in respect of landslide hazards. Probabilistic three-dimensional stability models have also been used by Al-Homoud and Tahtamoni (2000) to evaluate the probability of earth slope failure under seismic loading. The models were incorporated in an expert system SARETL (Stability Analysis and Remediation of Earthquake-Triggered Landslides) for stability analysis and remediation of earthquake-triggered landslides. The system has the ability to:

a) Predict permanent deformations induced by landslides under seismic loading by means of both probabilistic and deterministic techniques.
b) Assess earthquake induced landslide hazards on major transportation routes.
c) Propose a mitigation strategy against landslides with remediation strategies.

"Soft Computing" Methods

Existing geological conditions and the environmental situation control the stability of natural slopes. These conditions can hardly be described with precise figures thus making their representation quite vague in the analysis of the stability of natural slopes. Ni et al (1996) have exploited this vagueness in an artificial neural network using fuzzy parameters for the evaluation of stability of natural slopes.

The tool CSEES (Cut Slopes and Embankments Expert System), developed by Al-Homoud & Al-Masri (1999), is used for the evaluation of failure potential of cut slopes and embankments. They used fuzzy sets theory with modified Monte Carlo simulation technique to obtain the Slope Failure Potential Index.

Dodagoudar and Venkatachalam (2000) using Bishop's simplified method of stability analysis and the fuzzy sets theory, expressed the uncertain soil parameters as fuzzy numbers to carry out reliability analysis of slopes. The parameters considered are c'_1, ϕ'_1, c'_2 and ϕ'_2 and pore pressure ratio (r_u) which were assumed in the analysis for a two layer case where the subscripts 1 and 2 represent the respective layers.

Unless geological conditions such as discontinuities prevail, the critical slip surface in slope analysis is generally assumed to be circular. A good number of the procedures for the determination of the critical slip surface rely on traditional non-linear optimization techniques. The robustness of the algorithms of these methods for the determination of the global minimum factor of safety has been found to be questionable. Goh (2000) in a genetic algorithmic approach for such situations shows how the system is sufficiently suitable for layered soils.

4.5.3 Ground Improvement

Conventional knowledge-based systems

Construction in urban areas and the development of improved transportation links involves building works on soft clay deposits and other sub-quality materials. The limitations on space and or the extensive nature of these poor quality materials call for improvement in their properties if the proposed project has to be successful.

Ground improvement is described as the modification of existing site foundation soils or project earth structures so as to provide better performance under design and or operational loading conditions. Ground improvement techniques are increasingly used for new projects to allow utilization of sites with poor subsurface conditions and to allow design and construction of needed projects despite poor substratum conditions, which formally would have rendered the project economically unjustifiable. Several techniques of ground improvement exist and a number of analyses and decisions may be necessary to determine if ground improvement is even necessary and the methodology to adopt.

Knowledge-based systems development for ground improvement has been very limited. Moula et al (1995), Toll (1996b), document only a few of the known knowledge-based systems for ground improvement. IMPROVE (Chameau & Santamarina, 1989) and ESPGIS (Motamed et al, 1991) are the early developed knowledge-based systems for ground improvement. These systems advise on the selection of improvement techniques. EPSGIS has the additional ability of evaluating the suitability of the users' pre-selected technique.

"Soft Computing " Methods

Soil compaction is a common practice in engineering projects to improve the engineering properties of the soil for structures such as highway embankments and earth dams. In order to overcome the need to conduct the lengthy compaction tests on soils for earthwork structures, Najjar et al (1996) have used a neural network approach in predicting the compaction characteristics (OMC and MDD) of both natural and synthetic soils. The input parameters are the index properties of the soils such as classification data, consistency limits and specific gravity.

4.5.4 Retaining Structures

Conventional knowledge-based systems

There are various types of earth retaining structures and the selection of any for a particular problem depends on a number of parameters. Quite a few conventional knowledge-based systems (Hutchinson et al, 1987; Oliphant and Blockley, 1989; Arockiasamy et al, 1991) described in the literature are for retaining wall design and or selection. A few other conventional knowledge-based systems for retaining walls such as WADI (Chahine and Janson, 1987), and RETAIN (Adams et al, 1989) however differ in context as they are concerned with failure of the retaining wall.

Recently, Ranga, Rao and Sundaravadievelu, (1999) have used object-oriented technology with forward-chaining mechanism for the development of KNOWBESTD (KNOWledge based expert system for BErthing STructures Design) for the economic design of berthing structures. The emphasis of the design, however, is more on the structural components. The knowledge base consists of design procedures as specified by Indian Standard Codes and is represented in the form of demons and facts structured for the purpose of consultation using production rules. Retaining wall design has also been carried out by Zhu et al (2000) using an expert system ESEX. The system has the ability to select and then design the retaining structure. In this system, the heuristic aspects have been coded into facts and rules while the inference mechanism is based on the fuzzy-inference and the produce-inference.

CASTLES (Yau and Yang, 1998) is a case-based knowledge-based system for retaining wall selection. The knowledge base contains 254 previous retaining wall cases in Taiwanese design reports from which it identifies the most acceptable retaining wall systems for new projects.

4.5.5 Foundations Design

Conventional Knowledge-based Systems

Moula et al (1995) and Toll (1996a) have cited several knowledge-based systems in the literature in relation to foundations. These systems application fields include conceptual design, detailed design, pile driving and foundation construction. FOUNDCON (Rashad et al, 1991) aids the user in the selection of the most suitable foundation system for a particular problem. Izadi et al, (1995) present a knowledge based system for the design of shallow foundations using pressuremeter method. The system provides assistance in the planning of a site investigation, synthesis of the in situ test results and finally the selection of admissible foundations.

Hadipriono and Wolfe (1991) have demonstrated the use of angular fuzzy set models to assess the reparability of damaged foundations.

Toll and Barr (1998, 2000, 2001) in a knowledge-base system ConFound have provided a learning tool to students for the conceptual design of foundations. In a browsing mode, the system presents options while offering general hints to aid decision making thus acting in an advisory position. The system consists of three components namely; a database of project-specific information, knowledge base of foundation types and help files. ConFound is considered by its developers as a knowledge-base system shell as the information stored in it's various knowledge bases could easily be modified or striped to represent a different domain. In this light, Hamadto (2000, PhD Thesis) has shown the success of the shell in the development of a knowledge-based system that deals with swelling potential classification, heave prediction and foundation selection for expansive clay soils. The knowledge-based system recommends the most appropriate shallow foundation type based on the subsoil index properties and predicted heave potential.

"Soft Computing" approach

a) Fuzzy Sets

Several methods have been employed for the prediction of the load-carrying capacity of piles but one of the most successful methods is the use of fuzzy sets theory. Uncertainty in soil parameters such as the SPT- N value and the undrained shear strength (c_u) have been modelled with fuzzy numbers which together with other non-fuzzy parameters were used by Elton et al. (2000) for the calculation of pile bearing capacity.

b) Neural Network approach

Neural networks have been successfully used in the prediction of pile driving capacity and load capacities of driven piles in the mid-90s. Recently, Nawari et al (1999) introduced neural network paradigms for the design of piles subjected to axial and lateral loads using SPT-*N* values and the geometrical properties of piles. A feedforward Backpropagation Neural Network and Generalized Regression Neural Network approach was employed. Good correlation coefficients were obtained between the neural network models predicted pile capacities and measured values as compared to other empirical design formulas. The neural network approach was therefore considered to be more accurate than the commonly used techniques for the design of pile foundations. Rahman et al. (2001) have similarly used a back-propagation neural network model in predicting the uplift capacity of suction caissons. Suction caissons have found great use as anchor foundations for offshore structures in the oil and gas production areas. The system uses five input parameters namely:

a) The aspect ratio of the caisson
b) The undrained shear strength of the clay soil in which the caisson is installed
c) The relative length of the lug to which the caisson force is applied
d) The angle that the chain force makes with the horizontal and
e) The loading rate defined with respect to the soil permeability.

Predictions from the neural network model proved equally good or better than those of finite element based models.

4.6 Programme Implementation

There is a large record of number of knowledge-based systems that have been developed. There however appears to be no existing standards in their implementation. Most of the knowledge-based systems have been developed in LISP and PROLOG. Gallaire et al. (1984), Storey and Goldstein (1988) and Holsapple and Whinston (1995) all point out the appropriateness of PROLOG language for defining and implementing knowledge-based systems or expert systems in general. These languages have built-in data handling facilities.

4.7 Discussion

Knowledge-based systems technology has had a great impact on geotechnical engineering research. From the foregoing it is observed that the use of knowledge-based technology is widening in the geotechnical engineering field. In the initial stages of its introduction into geotechnical engineering, much attention was paid to the development of knowledge-based systems in the general site characterization domain. These range from systems for classification through parameter assessment to ground profiling. Indeed these knowledge-based systems together give a clearer view of the underlying ground thus facilitating better designs of civil engineering projects.

Knowledge-based systems developed for foundation problems and retaining structures basically play advisory roles in their design and or selection. In the case of slope design, conventional knowledge-based systems have been developed for stability analysis. Ground improvement has not seen much development in knowledge-based systems.

In recent time, there has been a drift from the conventional knowledge-based systems to other forms of Artificial Intelligence such as neural networks and fuzzy logic. This can be observed from the considerably large number of literature in the last part of the 90s and the early part of this millennium. Where parameter or behavioural prediction is necessary, neural network application appears to be more successful. The backpropagating neural network technique has been found to be most successful in most engineering application compared to other techniques. On the other hand fuzzy logic applications find their way into situations where uncertainties prevail. Better performance knowledge-based systems are obtained from hybrids of conventional knowledge-based systems approach with these other methods.

4.8 Conclusion

From the foregoing, there has been enough demonstration of knowledge-base systems technology in geotechnical engineering. The technology has been applied to various geotechnical fields such as soil characterization, retaining structures, foundations design and slope stability demonstrating the success of the field of knowledge-based technology in geotechnical research. It is not known which of the above systems if any is in operation as a commercial tool.

Although numerous knowledge-based systems have been developed for geotechnical engineering purposes, it must be emphasized that majority do not have a specific soil type in mind. Little attention has been paid to the fact that extensive soft soil deposits and other problematic soils underlie great tracks of land particularly along coastal areas, buried river channels and broad river floodplains where development is fast growing either due to constraints on land use or on purpose. These soils have their peculiar characteristics that planning geotechnical projects on such terrain can be a burden. The very low strength of soft clays (<50kNm^{-2}) for instance, calls for improvement in the strength characteristics for it to be capable of sustaining imposed load. The need to redirect attention to the development of knowledge-based systems for ground improvement must therefore be addressed.

It must however be highlighted that over reliance on the technology has the negative tendency of destroying future build up of human expertise due to continuous use of a particular system. As the technology gains popularity, consistent use will result in a stage where no human expert may be available to provide the domain knowledge for upgrading of existing systems.

The above analysis only aims to give an overview of the most important knowledge-based systems and is by no means exhaustive.

CHAPTER 5

DEVELOPMENT OF A DECISION SUPPORT SYSTEM FOR THE IMPROVEMENT OF PROBLEMATIC SOIL ENVIRONMENTS

5.1 Introduction

The first part of this chapter discusses the objectives of the research work and the criterion used for the selection of the expert system shell wxCLIPS which is used in the development of a decision support system for ground improvement.

This chapter is organized as follows: the objectives of the thesis are stated in Section 5.2. This is followed by a discussion on the development tool selection in Section 5.3. In this section, the reasons for which the wxCLIPS expert system shell was selected as the development tool for the ground improvement decision support system are highlighted. Two knowledge sources namely technical literature and domain experts that were extensively used for this research work are discussed in Section 5.4. Section 5.5 presents the implementation of the survey. Section 5.6 discusses the parameters used for the development of the knowledge-based system. In this section the characteristics that are used for the identification of the various problematic soils are discussed. The factors that are relevant for ground improvement methodology to be recommended and the improvement method selection procedure at a construction site are also described. Finally the conclusions drawn from this chapter are presented in Section 5.7.

5.2 Objectives of System Development

Ground improvement is becoming a common construction practice due to the limited availability of suitable space on the land surface and also the nature of certain types of facilities. Currently, only specialist contractors are involved in the implementation of any ground modification method. The consequences of any failures in design have catastrophic effects on human life and the function of the structure. It is therefore imperative that any ground improvement scheme should aim at ameliorating or averting such consequences.

As described in Chapter 2 there are many techniques of ground modification that can be applied to any particular ground situation. The selection of the most appropriate method applicable to a particular situation requires an adequate analysis. Examples of the questions that can arise are:

- How feasible is a particular method for the proposed facility?
- What degree of improvement will a particular method achieve?
- How economic is such a method?

Many more questions arise in the selection of the most appropriate method. It is therefore considered that some form of an assistant may be necessary to aid ground improvement experts in their decision making.

As noted in Chapter 2, a significant number of ground improvement methods have been applied in modifying the soil or ground conditions in order to achieve the expected performance level of an engineering facility and also for safety purposes. Some of these methods are applicable only under very limited poor soil conditions or few specified situations. The majority of the methods, however, has been used for the improvement of several types of poor soil or poor ground conditions for decades, and has also been used for different applications. The multiplicity of the methods and applications makes the decision process for selecting an appropriate improvement method very difficult. Depending on the difference in soil conditions, size of area to be improved, availability of construction materials, cost and a host of other factors, the degree of improvement achievable by a method, for example, may be site specific thus further complicating the decision-making process. An inadequate decision may result in very costly consequences that can have a devastating effect on the project life.

Only a few specialist contractors are engaged in ground improvement. Therefore, with the modern day continuous expansion of the construction of new projects, there is heavy demand on these few experts to meet project time schedules whiles guaranteeing efficiency of the method(s) in use and safety of the structure under consideration. This makes ground improvement technology expensive as the trade is in the hands of only the few experts. In the event of a significant loss of expertise to a ground improvement contractor through personnel changes, a further scarcity of expertise will exist.

Knowledge-based techniques have provided the opportunity for developing new decision support tools for the ground improvement domain expert that can be useful in his decision-making process and for storage of ground improvement data. Because of the requirement of assistance to aid the ground improvement project the aims of this thesis are:

- To store knowledge and data of the various traditional ground improvement methods and some innovative techniques developed over the years in the form of rules, which clearly define the ground improvement domain.
- Use a Knowledge-Based System (KBS) approach to select a suitable or appropriate ground improvement methodology for improving the physical properties of the ground or foundation soil for an engineering facility. It is envisaged that such an approach will improve efficiency in ground improvement practices in addition to time saving in ground improvement problem solving.
- The system is to assist ground improvement domain experts or specialists in their decision making when considering ground improvement alternatives in problematic soil environments. Such a decision support tool will boost the confidence of the expert in his choice of technique to be implemented.
- The system will also assist the domain expert in any modifications to the design of the selected method where necessary.
- To devise a method of knowledge dissemination for teaching purposes by means of a user-friendly teaching aid.

5.3 Development Tool Selection

One of the most crucial aspects in the development of a knowledge-based system is in the selection of a suitable tool commonly described as "shell" for the development. A shell is an environment built in a high level language that facilitates building expert systems, (Payne & McArthur, 1990). Unlike the early days of expert system development when building an expert system was from the scratch, there are now a number of shells available, either on a commercial basis or free distribution, that are specifically intended to assist in the building of expert systems or knowledge-based systems. As a result of this proliferation of shells, it is important therefore that the developer selects a tool that is most appropriate for the type of problem under consideration.

Several factors come into play in the selection of the most appropriate tool. Among these factors may include those outlined by Waterman (1986), Vedder (1989), and Edwards (1991), such as:

a) Size of system.

b) Variety of inference mechanisms and their control.

c) Ease of use.

d) Explanation facilities.

e) Uncertainty management.

f) Support and consultancy services.

g) Hardware requirements.

h) Price.

No one particular development shell may be found to satisfy all the above factors and others not listed. As a consequence, Citrenbaum et al (1990) suggested the chosen shell should be compatible and portable in knowledge representation with other products. An assessment of the usefulness of the selected tool in ground improvement was therefore necessary.

The expert system shell selected for this research work is wxCLIPS version 1.64. wxCLIPS is an extension to NASA's CLIPS expert system shell. It is essentially CLIPS, which has been modified to work with an event driven style of programming and a set of graphic user interfaces (GUI) functions.

CLIPS stands for C Language Integrated Production Systems. It is a multiparadigm programming language that supports rule-based, object-based and procedural programming paradigms. Since its creation in 1985, there have been many versions of CLIPS. The current version CLIPS 6.2 was released in May 2004.

The most fundamental reason for choosing wxCLIPS is the fact that wxCLIPS like the generic CLIPS is free. In addition to this, CLIPS is a general-purpose development environment and comes with the source code that can be modified or tailored to meet a user's specific needs. Further more, CLIPS has the ability of been embedded within procedural code, and integrated with other languages such as C, Java, FORTRAN, and ADA, thus making it portable and compatible with other products. Unfortunately however, the standard CLIPS shell lacks any facilities that can be used for the development of a user-friendly interface. As a result of this deficiency, it was thought that the wxCLIPS variant would be most appropriate as it extends CLIPS with functions that permit the construction of graphical user interfaces (GUI). The use of GUI would enhance the user-friendliness of the developed knowledge-based system for ground improvement to meet the objectives of the system development.

5.4 Knowledge Acquisition

Buchanan et al. (1983) have described knowledge acquisition as "the transfer and transformation of potential problem-solving expertise from some knowledge source to a program". This process according to Kidd (1987) is a critical stage in the building of an expert system as the power and utility of the resulting expert system largely depends on the quality of the underlying representation of expert knowledge. It is therefore imperative that the type and source of information be of the highest possible standard. In order to achieve this high quality of knowledge for a ground improvement decision support system, two sources of information gathering were employed namely:

a) Technical literature.
b) Domain experts.

5.4.1 Technical Literature

This formed an important source of information covering a very wide range of ground improvement techniques that are commonly used (termed traditional methods), innovative methods that have still not gained much acceptance in the field and also a host of methods that are laboratory based or only in the experimental stages. Technical literature sources include various geotechnical and soil mechanics textbooks, research papers from journals (such as Ground Engineering, Ground Improvement, Geotechnique, Computers and Geotechnics, etc.) symposia and conference proceedings, reference manuals (e.g. Eurocode 7: Geotechnical Design, British Standard Codes etc.) and online databases such as Elsevier, ScienceDirect and IngentaConnect. These publications have been a valuable source of information on various factors such as ground conditions, applicability of methods, design parameters, environmental concerns, contractual considerations and economic concerns which form the basic elements for a ground improvement method selection. Relevant information was abstracted from these publications following a thorough literature search for support knowledge enabling the generation of justifications and other explanations for the rules.

5.4.2 The Domain Experts

Much knowledge in the field of ground improvement technology can only be found by probing the minds of people currently involved in various ground improvement activities. Documentation of the newer techniques is very limited as such methods are still in the experimental stages or are yet to be generally accepted in the field of geotechnical engineering. The major source of knowledge therefore was private knowledge gathered from various domain experts with relevant hand-on experience and who have acquired their expertise from several years of working on various ground improvement projects. Expert assessments are often expressed in linguistic or imprecise terms (Elton et al., 1995; Tonon et al., 2000); however their knowledge is particularly useful in ranking rules and applying certainty to information within rules.

The numerous ground improvement techniques in the literature range from the traditional methods of preloading to various innovative methods including the use of additives such as fly ash. It is therefore possible that some specialization in the use of these methods exists among the various geotechnical engineering consultants or specialist contractors engaged in ground improvement practices. Two classes of specialist may therefore be identified. These are:

a) General-purpose consultant/contractor.
b) Specialist consultant/contractor.

Consultants or contractors that fall into the general-purpose consultant/contractor class are geotechnical engineering consultants or contractors whose practice is in the general geotechnical engineering field. Such specialists have a wide knowledge of most geotechnical engineering practices including some of the traditional ground improvement methods. The second class of consultants or contractors includes all personnel or contractors that specialize in one or more ground improvement techniques. Falling into this class is also the innovative ground improvement method expert who, through research and experimentation has developed a method that, though not classified among the traditional methods, is effective in its application. This latter class forms a small fraction of specialists in the field. Information from this class of specialist was considered critical for the purpose of this research. It was however thought appropriate to populate the ground improvement knowledge base with information from the two classes of domain experts having in mind the broad nature of ground improvement technology, the number of years of "on the job practice" a general purpose contractor or consultant may have had on the use of ground improvement technology and a host of other factors including the frequency of use of the method(s).

In order to authenticate and or augment the information gathered by use of the above relevant methods, it was further decided to conduct an interview stage of the knowledge elicitation process by focusing on domain experts from the specialist consultant/contractor class. Most of the information gathered from these experts however, was in the form of heuristics.

Knowledge elicitation according to Waterman (1986) has been a major problem in expert system development. This is due partly, to the unwillingness of experts to volunteer information in their domain areas in addition to the way in which they access their problem solving knowledge verbally, which typically is incomplete and unstructured. It is further known (Ericsson and Simon, 1980, 1984) that such data may be unreliable and contradictory. For any meaningful results therefore, a carefully planned strategy and systematic methodology of knowledge elicitation is necessary.

In the general knowledge elicitation process, the initial step involves the identification of a suitable domain expert. Because ground improvement is a specialized area in geotechnical engineering, it has also become the preserve of a few consultants and construction firms. Because of the economic situation, these specialists are constantly subjected to time constraints on the levels of ground improvement projects that time shedding to give information has been a difficult task. The approach adopted was therefore aimed at initially identifying experts in ground improvement technologies, contacting these experts with the view to identifying their operational areas, selecting the potential experts and finally arranging for dialogue with the willing expert(s).

The internet was resorted to as the most up to date source of information on ground improvement experts worldwide. Companies or consultants engaged in ground improvement practices in the UK in particular were additionally identified from the Ground Engineering Geotechnical Services File 2000 and the list of Federation of Piling Specialists. These lists keep comprehensive records of individuals and companies of good standing in geotechnical practices and who have been found to have high standards of technical ability, quality management and safety systems. In these records, apart from the contact details and numbers of employees of the firms, their areas of specialization are also listed. Other companies worldwide were identified through the internet.

Because ground improvement techniques are very numerous, it was decided for this research purpose that more than one domain expert would be required and that the domain expert would be somebody who has specialized in one or more ground improvement methods. As it would be difficult getting one domain expert knowledgeable in all the methods of ground improvement, it was further decided to employ the questionnaire method of knowledge acquisition as a means of reaching out to a large number of domain experts and also as a way of identifying the potential domain experts to interview.

5.5 Implementing the Survey

Knowledge extraction from the domain experts can be conducted in a number of ways. The most frequently used methodology is the compilation of a questionnaire, which is subsequently mailed to suitable domain experts. Interviews may also be conducted.

Implementing the survey was through the traditional methods of

a) Land mail
b) E-mail
c) Telephone.
d) In person

The mailing options, in particular e-mails, have the advantages of wider geographic coverage at minimum cost. E-mails are faster and have an added advantage over land mails of not getting lost in transit. Telephone communication is particularly useful for distant contacts though expensive. In situations where distance is not a problem, contacting the experts in person is most desirable.

In an anticipation of obtaining a good response in terms of numbers and relevance from the participants, no cost terms were considered important in determining the most appropriate method of contact with the experts. All the above forms of contact were employed though at different levels and intensity of use.

In order to get a view of the existence of any regional practices in the world, formal letters were sent to the identified personnel, construction companies and consultants associated with any form of ground improvement technology in various countries in Europe, Africa, America and Asia. This approach was thought would enable the capture of a wide variety of knowledge based on local experience to be stored in the database. Respondent construction firms and consultants were then served with the questionnaire. A total of 75 domain experts or specialist contractors were issued with the questionnaire. Following the response to the questionnaire, visits and or telephone conversations were then arranged with some of the experts.

The questionnaire was designed to comprise two parts, Part 1 and Part 2 (Appendix A). Part 1 consisted of general questions that were meant to gather information on the factors that were important in identifying the need for a ground improvement strategy for any particular facility. In this part participants were asked to select from a list of ground improvement techniques the ones they have used in the past, the reasons for the decision to use a particular method and the type of application for which the method(s) was (were) used. Part 2 of the questionnaire was more focused on the most popular ground improvement techniques that are currently been used.

The objective of splitting the questionnaire into these two parts was two fold namely:

a) to identify the operational areas of the responding participants and
b) to direct the relevant second part of the questionnaire to the respondents based on their domain areas.

This technique was chosen in order to generate the interest of experts and to allow free expression particularly in the innovative methods when answering the questionnaire, to maximize the chance of interaction with the expert rather than to bore the participants with questions that fell far outside of their specialized fields. For instance a consultant whose expertise is in the stone column design area of ground improvement would probably not concern himself with a questionnaire that seeks information on the electro-osmosis method.

Since ground improvement is a very specialized area of geotechnical engineering, the two common types of question format, namely open-ended and close-ended questions, were used. Close-ended questions are simple and straightforward demanding a yes or no answer, or making a choice from a number of answers provided. Such questions are easy to answer by the respondents as less time is used answering them. However, questions of this nature do not provide adequate information, for example if the ground is inhomogeneous a yes or no answer to a particular question may be too simplistic and the question may not even be applicable. Conflicting responses could therefore result from the respondents due to variations in the situations under which the methods might have been applied taking cognizance of the geographic spread of ground improvement experts relative to the spread of problematic soil types. The open-ended question format, which is a better way of gathering information from the domain experts, is time consuming to answer and more demanding in terms of information required. Many of the questions were set in this format with the view of obtaining diverse but realistic information from the specialists. Such diversity in opinion would be expected due to the local experience of the experts on the different problem soils. For example, minor variations in the properties of a problematic soil type at different locations on the globe could result in significant differences in the opinions of the different decision-makers on projects on these soils.

5.5.1 Lessons from the Survey

17 completed questionnaires representing 22.7% of the total number of questionnaires distributed was returned by land mail, facsimile or e-mail some with additional technical literature. Apart from two responses from the U.S.A, one each from Canada and Germany, the majority of the respondents are UK based (Table 5.1).

Organization	Location	Job Description
Fondedile Foundation Ltd	UK	Specialist Contractor
Geotechnics Ltd	UK	Specialists Consultants
Babtie Group	UK	Consultants
Roger Bullivant Ltd	UK	Specialist Contractor
Bachy Soletanche Ltd	UK	Specialist Contractor
W.A. Fairhurst & Partners	UK	Consultants
Building Research Establishment	UK	Consultant/Research Contractor
Pennine Vibropiling	UK	Specialist: Piling
British Drilling & Foundations	UK	Specialist Contractor
Stent/Hercules	UK	Specialist: Ground Engineering
URS Corporation Ltd	UK	Consultants
Parkman Ltd	UK	Specialist Contractor
Vibro Group	UK	Specialist Sub Contractor
Geopac West Ltd	Canada	Specialist Contractor
Moretrench Geotech	U.S.A	Specialist Contractor
Rembco Geotechnical Contractors Inc.	U.S.A	Specialist Contractor
Management Variations in Construction	Germany	Contractor

Table 5.1: Ground Improvement Questionnaire Response.

The responding experts can be classified into three geotechnical categories namely the General Consultant, the Specialist Consultant/Contractor and a third smaller category the Research Contractor. In view of the difficulties apparently associated with ground improvement experts as stated in Subsection 5.4.2, the response was considered appropriate for the purpose of this research.

A few lessons taken from the survey may be summarized into the following:

- Selection of the right contact personnel.
  In many situations, letters addressed to the directors of firms were either ignored or responded to by non-professionals. A few organizations to which mails were sent were not actually involved in any ground improvement projects even though internet sources might have indicated so.
- Using the right vehicle.
  This may be subdivided into
  a) Human perception based on the way people received the message and interpreted it. It is important to state that while some experts embraced the idea of building the knowledge-based system for ground improvement, and were very willing to contribute their expertise to its successful construction others were simply sceptical or unwilling to provide any information.
  b) Individual opinions
     - The several categories experts fit into such as general, specific technology and innovative technology. This however, is not discernable at the beginning of the survey when very little information of the background of the experts is known.
     - Differences in the opinions of the experts on any particular issue regarding ground improvement. This is manifested on the choice of ground improvement they may make when the individuals are asked to make a choice of ground improvement for a particular soil condition.
  c) The choice of questionnaire format. Since most of the questions were in the open-ended format, it is thought that fewer than expected number of parties to whom the questionnaire was posted had the time to answer the questions due to their work schedules.

5.5.2 The Interview.

Information gathering according to Waterman (1986), Payne & McArthur (1990), may be by conducting interviews (asking the expert questions) or by observation, observing the expert at work with only occasional (minimal) interruptions to clarify what is happening. Where applicable, interviews may be conducted on-site. Allwood (1989) identifies two forms of the interview namely:

- Unstructured general interviews.
- Interviews focused on one goal or type.

Unstructured interviews are conducted in the initial stages and are designed to centre on information gathering with the view to enabling participants familiarize themselves with each other's jargon. In the focused interviews, the interviewer concentrates on a specific problem at a time mindful of the symptoms and rules, which confirm that goal alone. This form of the interview is usually quickly blended with the unstructured interviews. Detailed examination of any informational materials the experts may use is an added opportunity of knowing how the experts work. Such materials may include manuals, textbooks, computer printouts, schematic diagrams and memos.

Aides such as video and tape recorders may be used for the interview, however, with the consent of the domain expert. One major advantage derived from this approach is that every single word or action is kept on record. Payne and McArthur (1990) however cite the disadvantages as follows. That:

a) A tape must be transcribed and a video logged and then the large volumes of material analyzed for useful information.
b) There is only a small percentage of useful material in addition to that obtained during the interview in comparison to the cost in time and money for the process.

Notwithstanding these disadvantages Payne and McArthur (1990), allude to the suitability of this approach in situations where the expert is imparting large quantities of detailed information.

Potential sources of errors that may be associated with the expert's information may include the following:

a) Careless mistakes made by the expert while performing a task during the observation.
b) Experts may say things they don't mean.
c) Experts may sometimes make mistakes because their own knowledge is faulty.
d) The interviewer may misinterpret the expert.

As a consequence, the validity of information gathered after each interview, must be determined by the knowledge engineer.

Following responses from the correspondences, questionnaire and telephone calls four domain experts based in the UK whose expertise was found to be vital in the building of the knowledge-based system for ground improvement were identified for the interview stage of information gathering. The knowledge areas of the selected experts are shown in Table 5.2. A series of face-to-face and telephone interviews with these experts were arranged on individual basis over a three-month period.

Interviewee	Major Function	Knowledge Area	
		Common to all	Variation
A	Consultant	Dynamic Compaction Vibrocompaction Vibro-replacement Preloading/Surcharge Drainage Techniques Bulk Grouting, Jet Grouting Soil & Rock Anchors Geosynthetics, Soil Nailing Micropiles	Mechanically Stabilized Earth Structures (MSE) Vibro Concrete Columns Compensation Grouting Fissure Grouting Inundation
B	Consultant	As in A (except Jet Grouting)	Stone and Lime Columns Lime Piles Vibro Displacement Deep Soil Mixing Shallow Soil Mixing
C	Consultant	As in A (except Drainage Techniques, Micropiles,)	Permeation Grouting Vibro Concrete Columns
D	Consultant, Research Contractor	As in A (except Jet Grouting, Bulk Grouting , Micropiles, Soil Nailing, Soil & Rock Anchors)	Rapid Impact Compaction Deep Soil Mixing

Table 5.2: List of Interviewed Experts and their Knowledge Areas.

For the purpose of this work, it was appropriate to conduct the interviews with a mixture of the above-mentioned techniques. All interviews proceeded in much the same way. Unstructured interviews were carried out during the first few interviews with the identified domain experts. During these interviews information about their areas of operation, the ground improvement techniques they were commonly involved in, the frequency of usage of the methods, reasons why ground improvement methodology may be a better option than other construction methods such as piling or complete removal of problem soil were sought. The aim of this approach was to identify in broad terms the reasons for using ground improvement approach for solving certain foundation problems.

In the subsequent structured part of the interview, the experts were asked to react to a series of open questions on the ground improvement methods they were most familiar with. Details of the soil conditions under which the methods are used singly or in conjunction with other methods, the most important reasons for selecting a particular method for a specific situation and the technical details of the methods were sought.

A tape recorder was used to record some of these sessions to serve as a back up but the quality of the recording appeared too poor to be useful. Important materials such as publications and drawings were provided by some of these domain experts. These formed an added source of information. Table 5.2 shows the areas of ground improvement that the interviewees have special knowledge and have contributed their expertise for this research. The methods listed in column 3 are those that all the interviewees have good knowledge about except a few.

5.6 Establishing the Basic Parameters.

The effective use of expert system shells revolves around the correct representation of rules and knowing how the shell operates on these rules. This calls for a proper analysis of any knowledge gathered in order for it to be represented correctly. The knowledge from the two sources (technical literature and ground improvement experts) was therefore analyzed in order to obtain a more objective perspective of the most appropriate ground improvement expertise.

For a successful representation of the rules relevant to ground improvement technology, two main areas were considered significant namely:

- A preliminary evaluation process
- The improvement method selection process.

The preliminary evaluation process precedes the method selection process.

5.6.1 The Preliminary Evaluation Process

This process is concerned with identification of the problematic ground with the view to establishing the need for ground improvement should conditions favour this process. Ground improvement should be recommended only under situations where poor soil conditions exist at a site earmarked for the location of a facility and where the approach should be found to be the best economic option. The first step therefore is concentrated on establishing if a problem soil is present in the site that could pose major problems in the performance of the facility. Soil identification is usually carried out through thorough site investigation procedures. The main objectives of the site investigation according to British Standard BS 5930 (1981), *Code of practice for site investigations* are to:

a) Assess the general suitability of the site for the proposed development;
b) Enable an adequate and economic design to be prepared;
c) Foresee and provide against difficulties that may arise during construction due to ground and other local conditions;
d) Predict any adverse effect of the proposed construction on neighbouring structures.

Data for this part of the research was obtained from the existing technical literature on various soil classification schemes. Such sources include The British Standard BS 5930 (1981), *Code of practice for site investigations,* and Laboratoires des Points et Chaussées classification scheme, and the Unified Soil Classification System (USCS) among others. The Unified Soil Classification System (USCS) was adhered to for the classification of the major soil groups.

The main parameters under consideration can be classified under four categories namely:

a) Soil index properties such as grain size, plasticity, void ratio, water content, density.
b) Soil mechanical properties such as shear strength, effective cohesion, bearing capacity, compressibility.
c) Chemical properties such as acidity, sulphate content, organic content.
d) Permeability and consolidation properties.

The relevant data on these parameters have been obtained from site investigation reports and several correlation charts drawn by various researchers. The aim of gathering such information was to identify any characteristics that would result in settlement, stability and bearing capacity problems should there be the need to establish any structure at a site with such characteristics.

As noted in Chapter 2, soils classified as problematic soils include:

a) Weak and compressible soils
b) Expansive soils
c) Collapsible soils
d) Frozen soils
e) Corrosive soils
f) Organic soils
g) Liquefiable soils

The basic identification procedures for these soils are given below.

Weak and Compressible Soils

Soils classified under this category include soft clays, sensitive clays, organic clays and silts, and peat. Such soils often tend to occur in flat, low-lying areas, estuaries and old lakebeds. They generally have low strength values.

Identification of these soils may be done by simple field tests such as the standard penetration test to obtain the *N*-value or laboratory tests such as the undrained shear strength test. Tables 5.3 and 5.4 below illustrate some of the properties of these soils.

Consistency	Description		
	Field Test	Undrained Shear Strength Range, S_u (kN/m^2)	Equivalent *N** value (very approximate)
Very Soft	Exudes between fingers when squeezed in hand	<20	<2
Soft	Moulded by light finger pressure	20 – 40	2 – 4
(soft to firm)		(40 – 50)	
Firm	Can be moulded by strong finger pressure	50 – 70	4 – 8
(firm to stiff)	Cannot be moulded by fingers	(75 – 100)	
Stiff	Can be indented by thumb	100 – 150	8 – 15
Very stiff or hard	Can be indented by thumb and nail	> 150	>15

Note: * *used only as a preliminary evaluation of clay consistency.*

Table 5.3: Consistency of Clays (adopted from Weltman and Head, 1983)

S. No	Consistency	q_u (kN/m^2)	Characteristics
1	Very soft	<25	Fist can be pressed into soil
2	Soft	25 – 50	Thumb can be pressed into soil
3	Medium	50 – 100	Thumb can be pressed with pressure
4	Stiff (firm)	100 – 200	Thumb can be pressed with great difficulty
5	Very stiff	200 – 400	The soil can be readily indented with thumb nail
6	Hard	> 400	The soil can be indented with difficulty by thumb nail

Table 5.4: Consistency of Clays in Terms of Unconfined Compressive Strength, q_u (adopted from Arora,1989).

The undrained shear strength, S_u, and the unconfined compressive strength, q_u, are the main criteria used in the identification of soft clays. A soil with an undrained strength value of 50kN/m^2 or less suggests the soil is soft. According to Terzaghi and Peck (1967), clay is regarded as very soft if its unconfined compressive strength is less than 25kN/m^2 and as soft when the strength falls in the range of 25 to 50kN/m^2. Kamon and Bergado (1991) however identify soft ground based on the type of facility as outlined in Table 5.5. Based on their criteria soft ground for express highways, railways and river dykes is identified mainly by the SPT *N*-value.

Structure	Soil Condition	Parameter			
		SPT *N*- value	Undrained Shear strength (S_u) kN/m^2	Unconfined Compression strength (q_u) kPa	Water content %
Road	A: Very Soft B: Soft C: Moderate	<2 2 - 4 4 - 8	<25 25 – 50 50 - 100	<125 125 – 250 250 - 500	
Express Highway	A: Peat Soil B: Clayey Soil C: Sandy soil	< 4 < 4 <10			>100 >50 >30
Railway	Layer Thickness >2m >5m >10m	 0 < 2 < 4			
Bullet train	A B	<2 2 - 5		<200 200 - 500	
River Dyke	A: Clayey Soil B: Sandy Soil	<3 <10	<60		> 40
Fill Dam		<20			

Table 5.5: Identification of Soft Ground (adopted from Kamon and Bergado, 1991)

From Tables 5.3 - 5.5 cohesive soils with SPT *N*-value of 4 and below are classified as soft for the purpose of this study. In addition, the undrained shear strength and unconfined compressive strength are taken as 50kN/m^2 or below.

In the case of granular soils the concept of compactness (Relative Density) is used as a descriptive term correlated with some other strength and deformation soil characteristics to describe soil weakness. Table 5.6 illustrates these descriptive terms in terms of relative density and SPT *N*-values.

Relative density (%)	Descriptive term	*N*-Values
0 - 15	Very loose	0 – 4
15 - 35	Loose	4 – 10
35 - 65	Medium dense	10 – 30
65 - 85	Dense	30 – 50
85 - 100	Very dense	> 50

Table 5.6: Descriptive Terms for Relative Density with Equivalent SPT N–Values (adopted from Carter & Symons, 1989)

"Compactness" is described as the extent to which granular soils are compacted together in their natural state or in terms of relative density D (Carter & Symons, 1989) as follows

$$D=\frac{e_{max}-e}{e_{max}-e_{min}}=\frac{\gamma_{max}}{\gamma}=\frac{\gamma-\gamma_{min}}{\gamma_{max}-\gamma_{min}} \qquad (5.1)$$

Where

e = volume of voids in soil natural state

e_{max} = voids ratio of soil in its loosest state

e_{min} = voids ratio of soil in its densest state

γ = dry density of soil in its natural state

γ_{max} = dry density of soil in its loosest state

γ_{min} = dry density of soil in its densest state

Thus a soil in its loosest state has a relative density of 0%, while a value of 100% represents a soil in its densest state. Granular soils with relative density below 35% are suggestive of loose soil or very loose soil. The corresponding SPT *N*-value for soils identified as loose granular is below 10. These values were therefore adopted as the upper limits for the identification of weak granular soil using the above parameters.

Sensitive clays

Sensitive clays are generally identified by their sensitivity (S_t) defined by

$$s_t = \frac{Natural\,Shear\,Strength}{\mathrm{Re}moulded\,Shear\,Strength} \tag{5.2}$$

The value of S_t for normal clays is commonly between 2 and 4. Clays with sensitivity values of 4 – 8 are considered sensitive. Table 5.7 shows the classification of sensitive clays by various investigators.

Sensitivity	Description			
	Skempton and Northey (1952)	Rosenqvist (1953)	Söderblom (1969)	
			Sensitivity	Classification
< 1	Insensitive	Insensitive	<20	Normal
1 – 2	Low Sensitivity	Slightly Sensitivity	20 – 50	Semi Quick
2 – 4	Medium Sensitivity	Medium Sensitivity	> 50	Quick Clays
4 – 8	Sensitive	Very Sensitive		
8 – 16	Extra Sensitive	Slightly Quick clays		
> 16	Quick Clays	-		
(16 – 32)	-	Medium Quick clays		
32 – 64	-	Very Quick Clays		
> 64	-	Extra Quick Clays		

Table 5.7: Classification of Sensitivity of Clays.

Sensitivity classification of clays based on Söderblom (1969) significantly differs from the classifications based on Skempton and Northey (1952), and Rosenqvist (1953). In the Söderblom (1969) classification, clays with sensitivity above 20 may be considered problematic as they fall into the semi quick or quick clay groups.

For the purpose of this work sensitive clays are identified as clays with sensitivity of 1 and above in accordance with the Skempton and Northey (1952) and the Rosenqvist (1953) classification schemes.

Compressible soils

These soils are identified by their compressibility. Compressible soils generally have their coefficient of volume compressibility, m_v, above 0.1m^2/MN. Typical values of m_v for various soils are shown in Table 5.8

Clay type	Compressibility	Coefficient of volume compressibility m_v (m^2/MN)
Very heavily overconsolidated clays, stiff weathered rocks, some tills	Very low	< 0.05
Heavily overconsolidated clays, some tills, hard London clay and stiff tropical red clays	Low	0.05 – 0.1
Overconsolidated clays, such as London clays, some glacial clays	Medium	0.1 – 0.3
Normally consolidated clays (e.g. alluvial or estuarine)	High	0.3 – 1.5
Highly organic alluvial clays and peats.	Very High	> 1.5

Table 5.8: Typical Values of Compressibility of Cohesive Materials (adopted from Weltman and Head, 1983)

The results in Table 5.8 indicate that compressibility is a phenomenon associated with normally consolidated and overconsolidated clays, some organic clays and peat.

Expansive Soil

Nelson and Miller (1992) describe expansive soil as any soil or material that has a potential for shrinking or swelling under changing moisture conditions. Jones and Holtz (1973) have indicated that these soils cause more damage to structures, in particular light buildings and pavements, than any other natural hazard. Expansive soils are distinguished from other soils by their ability to swell when they imbibe water and the consequent volume change.

The most widely used parameters for identifying expansive soils are the soil index properties such as the grain size distribution, clay content and plasticity. Other soil properties such as the cation exchange capacity (CEC) and saturation moisture have been cited (Gill and Reaves, 1957) as some of the most representative properties that may be used in the estimation of swelling potential of soils. McCormack and Wilding

(1975) report the use of clay content as a reliable method of predicting swelling potential of soils. Soils that are expansive must have a significant proportion of clay and probably fall within the Unified Soil Classification System of CL (clays of low plasticity) or CH (clays of high plasticity). The Atterberg limits test, however, forms the most popular approach in predicting the swell potential of soils. Table 5.9 illustrates the use of these limits (Liquid Limit, w_L; Plasticity Index, w_P) in addition to proportion of colloids and the shrinkage limit for classification of expansive soils by Holtz (1969), and Gibbs (1969), following tests on undisturbed soil samples.

Colloids %	Plasticity Index %	Shrinkage limit %	Liquid Limit %	Swelling potential
>28	>35	>11	>63	Very High
20 – 31	25 – 41	7 – 12	50 – 63	High
13 – 23	15 – 28	10 – 16	39 – 50	Medium
<15	<18	<15	<39	Low

Table 5.9: Expansive Soil Classification Based on Common Soil Tests (adopted from Holtz, 1969 and Gibbs, 1969).

Several other classification schemes based on parameters similar to those above have been used to identify expansive clays. Tables 5.10 to 5.15 show some of these classification systems.

Plasticity Index (I_P) (%)	Clay fraction (%)	Shrinkage Potential
>35	>95	Very high
22 – 48	60 – 95	High
12 – 32	30 – 60	Medium
<18	<30	Low

Table 5.10: Expansive Soil Classification (adopted from Building Research Establishment, 1980).

Linear Shrinkage	Shrinkage limit (%)	Probable Swell (%)	Degree of expansion
<5	>12	<0.5	Noncritical
5 – 8	10 – 12	0.5 – 1.5	Marginal
>8	<10	<1.5	Critical

Table 5.11: Expansive Soil Classification based on Shrinkage limit or Linear Shrinkage (after Altmeyer, 1955)

Swell Potential (%)	Swell Classification
<0.5	Low
0.5 – 1.5	Marginal
>1.5	High

Table 5.12: Expansive Soil Classification based on Linear Shrinkage (after Arnold, 1984)

Linear Shrinkage (%)	Potential Swell (%)	Description
5 - 8	< 7.5	Low
8 – 12.5	8 – 15	Medium
12.5 – 17.5	16 – 30	High
>17.5	>31	Very High

Table 5.13: Expansive Soil Classification based on Swell Test at In-situ Overburden Stress (after Snethen, 1984)

Plasticity Index (%)	Swelling Potential
0 – 15	Low
10 – 35	Medium
20 – 55	High
35 and above	Very high

Table 5.14: Expansive Soil Classification based on Plasticity Index (after Chen, 1988)

In addition to the above, the Expansion Index test [ASTM D4829] (ICBO, 1991; Anderson and Lade, 1981) is used to describe the amount of swell in terms of the Expansion Index (EI).

The Expansion index EI, is given by

$$\text{EI} = 1000\, h\, F \qquad (5.3)$$

Where:

EI = Expansion Index

h = expansion of soil (in)

F = percentage of the sample by weight that passes through a #4 sieve

The classification of soils by expansion index (EI) is given in Table 5.15

EI	Potential Expansion
0 – 20	Very Low
21 – 50	Low
50 – 90	Medium
91 - 130	High
>130	Very high

Table 5.15: Interpretation of Expansion Index Test Results (ICBO, 1997)

According to ASTM, "The expansion index has been determined to have a greater range and better sensitivity of expansion potential than other indices" (such as Atterberg limits). Soils with EI of 91 and above are highly expansive. Based on this index soils with EI below 50 may be regarded as having low to very low expansion potential.

The activity of clay is also a widely used property in predicting swell potential of clays. Activity (A_c) of a soil is defined as the ratio of soil plasticity index (I_p) and the percentage of clay fraction (F). i.e.

$$A_c = \frac{Ip}{F} \tag{5.4}$$

Thus by combining the Atterberg limits and clay content of a soil a single parameter, the Activity is obtained.

Indeed, the amount of water in a soil mass depends upon the type of clay mineral present. Activity is a measure of the water-holding capacity of clayey soils. The changes in the volume of a clayey soil during swelling or shrinkage depend upon the activity (Arora, 1989). Soils containing the clay mineral montmorillonite have activity greater than 4. If kaolinite is the major clay mineral of the soil, the activity is generally below 1. Soils with the clay mineral illite have activity between 1 and 2. The classification of soils based on activity is shown in Table 5.16 and Figure 5.1

Activity (A_c)	Soil Type
< 0.75	Inactive
0.75 – 1.25	Normal
> 1.25	Active

Table 5.16: Classification of Soils Based on Activity (after Arora, 1989).

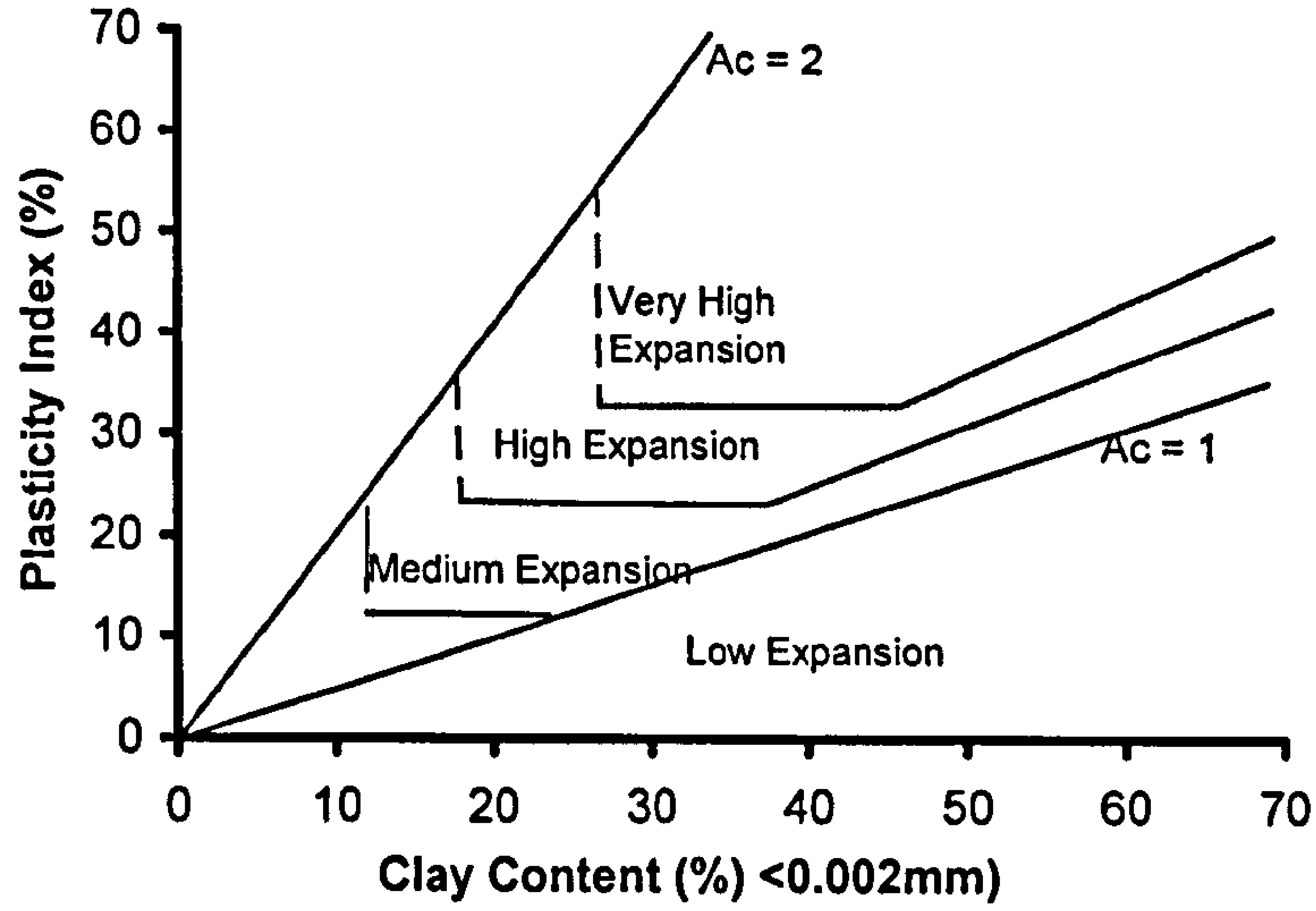

Figure 5.1: Estimation of the Degree of Expansiveness of a Clay Soil (after Williams and Donaldson, 1980)

Sowers' classification Table 5.17 describes the volume change susceptibility of soils based on the plasticity index and shrinkage limit with regional bias.

Likelihood of volume change with change in moisture	Plasticity Index (%)		Shrinkage Limit
	Arid region	Humid region	
Little	0 – 15	0 – 30	≥ 12
Little to moderate	15 – 30	30 – 50	10 – 12
Moderate to severe	≥ 30	≥ 50	≤ 10

Table 5.17: Volume Change Susceptibility of Soils (adopted from Sowers, 1962)

Schafer and Singer (1976) have however shown that the clay type is an important indicator of the expansion potential of a soil in comparison to the clay content.

In all these classification schemes, the various researchers have drawn conclusions on the parameters they have used to be the best indicators of potential swell.

It is observed from the foregoing classification schemes that there is no uniformity or accepted standard in the various classification schemes even with the same parameters. To illustrate this, Table 5.18 compares the use of Plasticity Index for the classification of expansive soils by Holtz 1969, Gibbs 1969, BRE 1980 and Chen 1988.

Plasticity Index (%)			Classification
Holtz (1969), Gibbs (1969)	BRE (1980)	Chen (1988)	
>35	>35	>35	Very High
25 – 41	22 – 48	20 – 55	High
15 – 28	12 – 32	10 – 35	Medium
<18	<18	0 - 15	Low

Table 5.18: Comparison of Expansive Soil Classification based on Plasticity Index.

There are disparities in the upper and lower limits of the plasticity indices of the various expansive soil classes in the classification systems presented except for soils with very high expansion potential. 35% is generally accepted as the lower limit of the plasticity index for such soils. Consequently this value has been adopted for the purpose of this work as the minimum value of the plasticity index of soils with very high expansion potential.

The boundary between each class of expansive soil and the next within the same expansive soil classification system is also very vague. For instance soils with plasticity index of 32% could be classified as having either medium or high expansion potential in both the BRE (1980) and Chen (1988) expansive soil classification systems. The differences in the remaining classes shown in the table are however very narrow.

Kariuki and van der Meer (2004) attribute these differences to variations in sample conditions in the different swell tests (i.e. disturbed or undisturbed samples) in addition to testing factors over wide range of values. Using a variety of soil properties (physical, chemical and mineralogical) and various methods of testing on soils from three physiographic zones namely high ground (Volcanics), plains and high ground (basement rocks), they have proposed a unified Expansive Soil Indices (ESI) for the classification of swell potential of soils (Table 5.19) as a means of establishing a standardized approach to the determination of the swelling potential of expansive soils.

ESI-1	ESI-2	ESI-3	Rating	Mineralogy
< 1.15	< 1.10	< 0.5	Low	Kaolinite
1.15 – 2.15	1.1 – 2.0	0.4 – 1.0	Moderate	Illite/mixed layer minerals
> 2.15	> 2.0	> 1.0	High	Smectites

Table 5:19: Classification Thresholds based on ESI (after Kariuki & van der Meer, 2004)

Their proposal is based on properties such as particle size distribution, the Atterberg limits, linear extensibility, the soil cation exchange capacity, exchangeable bases and saturation moisture of the soils, which have been used in the determination of other soil indices relevant in the estimation of ESI. ESI is calculated from the following:

$$\text{ESI-1} = A_c + \text{CEA}_c + \text{SSP} + \text{LEP}_c \qquad (5.5)$$

$$\text{ESI-2} = A_c + \text{CEA}_c + \text{SSP} \qquad (5.6)$$

$$\text{ESI-3} = \text{SSP} \qquad (5.7)$$

Where A_c = Activity

CEA_c = Cation exchange activity

SSP = Saturated standard moisture

LEP_c = Linear extensibility percentage due to clay

These indices reflect the number of available measurements and should be used for different levels of risk estimation. ESI-3 is used as a quick reconnaissance field index, while ESI-1 is for more elaborate site investigation.

They conclude that swelling potential of soils is mainly dependent on the clay type and consequently indices indicative of the clay type would generally be good indicators in the establishment of a unified expansive index.

In comparison to the other classification schemes above, the use of ESI for the identification of expansive soils may be a better approach as the expansion index is obtained after a consideration of several soil parameters.

Collapsible Soils

Laboratory identification of collapsible materials is usually done by means of the swell-consolidation tests, soil density, liquid limit, gradation analysis, porosity and void ratio. Soils susceptible to large collapse are identified using density criteria. Their identification is therefore based on the same descriptive terms as in the case of weak granular soils. In situations where the density is sufficiently low so that the void space is larger than needed to hold liquid limit water content, then collapse problems are likely. Collapse is not likely if the void space is less than that needed for the liquid limit water content unless the soil is loaded. Collapsible soils thus have loose structures and bulky shaped grains. The soil state parameters namely density, void ratio and plasticity are therefore the essential characteristics that may be used in their identification.

The compactness of soils is determined in terms of relative density established from in-situ tests such as SPT or static penetrometer. Descriptive terms used with the STP *N*-value and other tests and sand properties suggested by Nixon (1982), are given in Table 5.20. From the table, soils that classify as loose soils based on the established correlation parameters may be regarded as collapsible soils but with further considerations in terms of collapse potential and the saturation state of the soil.

Description	Very Loose	Loose	Medium Dense	Dense	Very Dense
SPT *N*-value (blows/0.3m)[a]	<4	4-10	10-30	30-50	>50
CPT cone resistance (MN/m^2) [b]	<5	5-10	10-15	15-20	>20
Equivalent relative density (%)[c]	<15	15-35	35-65	65-85	85-100
Dry unit weight (kN/m^2)	<14	14-16	16-18	18-20	>20
Friction angle (degrees)	<30	30-32	32-35	35-38	>38
Cyclic stress ratio causing liquefaction (τ / σ_0')	<0.04	0.04-0.10	0.10-0.35	>0.35	-

Table 5.20: Description of Soils in Terms of Compactness (after Nixon, 1982).

Notes: a = At an effective vertical overburden pressure of 100kN/m2

b = *No unique relationship exists between CPT and SPT values – It should be reassessed at each site*

c = *Freshly deposited, normally consolidated sand.*

Soils susceptible to collapse are further identified by the collapse potential (CP) defined by:

$$CP = \frac{\Delta e_c}{1+e_0} = \frac{\Delta H_c}{H_0} \tag{5.8}$$

Where CP = collapse Potential

Δe_c = Void ratio upon wetting

e_0 = Initial void ratio

ΔH_c = specimen height change upon wetting

H_0 = initial specimen height

Evaluation of collapse potential can be carried out by the standard consolidation test. Table 5:21 illustrates the collapse potential of soils. Soils with CP above 1% may pose problems to a proposed structure upon wetting or saturation. Consequently a collapse potential of 1% is taken as the minimum value of this parameter for the identification of a collapsible soil.

Collapse Potential (CP) %	Severity of Problem
0 – 1	No problem
1 – 5	Moderate trouble
5 – 10	Trouble
10 – 20	Severe trouble
>20	Very severe trouble

Table 5.21: Collapse Potential of Soils (adopted from Knight, 1963)

The likelihood of collapse can also be determined from the relationship

$$e_c = e_l \quad \text{(Denisov criteria)} \tag{5.9}$$

$$e_c = 0.85 e_l + 0.15 e_p \quad \text{(Feda criteria)} \tag{5.10}$$

Where e = natural void ratio

e_l = void ratio at liquid limit

e_c = critical void ratio

e_p = void ratio at plastic limit.

Organic Soils

Based on The Laboratoires des Points et Chaussées classification system, organic soils are classified as follows Table 5.22. In this system, the organic material content (MO) is the main criterion used for the classification of the soil. All soils with organic material content above 3 may be regarded as being organic. Descriptive terms such as slightly, moderately and very are used as the organic material content increases.

Material Content (MO) %	Description
< 3	Inorganic
3 – 10	Slightly organic
10 – 30	Moderately organic
> 30	Very organic

Table 5.22: Organic Soil Classification.

Alternatively, organic soils can be identified by performing two liquid limit tests, one on the natural soil sample from the field and another on an oven-dried sample (Coduto, 1999). The soil is considered to be organic if the liquid limit of the oven-dried sample is less than 75% of the original value.

Frost Susceptible Soils

Frost susceptibility tends to be associated with low and medium plasticity clays. The preliminary identification of frost susceptible soils can be done by correlation between the grading and plasticity index (PI) (Carter and Symons, 1989) as shown in Table 5.24.

Permeability rating	Identification	Frost Susceptibility
High Permeability	Granular: < 10% finer than 75μm	Not Susceptible
Intermediate Permeability	Granular: ≥10% finer than 75μm	Susceptible
	Cohesive: PI < 20	
Low permeability	Cohesive: PI ≥ 20	Not Susceptible

Table 5.24: Frost Susceptibility of Soils (adopted from Carter and Symons, 1989).

In this regard, granular soils with 10% or more material finer than 75μm and cohesive soils with plasticity index of less than 20% may be frost susceptible. Table 5.25 illustrates the classification of frost susceptible soils by The U.S Corps of Engineers. The classification is more elaborate than that due to Carter and Symons (1989). Four groups of frost susceptibility denoted by F1, F2, F3 and F4 are defined. The two systems of classification are based on the grain size distribution for granular soils and the plasticity index when cohesive materials are involved.

Group (Increasing susceptibility)	Soil type
F1	Gravely soils with 3 – 20 % finer than 0.02mm
F2	Sands with 3 – 15 % finer than 0.02mm.
F3	a) Gravely soils: >20% finer than 0.02mm
	b) Sands (except fine silty sands): >15% finer than 0.02mm
	c) Clays with PI > 12 except varved clays
F4	a) Silts and sandy silts
	b) Fine silty sands: >15% finer than 0.02mm
	c) Lean clays with PI<12
	d) Varved clays: with non-uniform conditions

Table 5.25: Frost Susceptibility of Soils According to the US Army Corps of Engineers (adopted from Mitchell, 1993).

A shallow ground water table or water infiltrating from the ground surface must be present to provide water for freezing.

Liquefiable soils

According to Coduto (1998), liquefaction occurs only when the following criteria are met.

a) Soil must be cohesionless (i.e. $c = 0$).
b) Soil must be loose (relative density should be less than 1).
c) Soil must be saturated.
d) Earthquake produces ground shaking with sufficient intensity and duration.
e) Ground shaking produces undrained conditions.

5.6.2 Assessment of Problem

Having established evidence of the presence of any of the aforementioned problem soils at the site under consideration, the next step is to assess the damage potential due to these soils to the intended facility.

The assessment is in terms of stability of slopes, bearing capacity and settlements, seepage and liquefaction. Summaries of the various parameters under consideration are given in Appendix B.

According to Department of The Army (1999), the slope stability analysis is based on the following cases:

a) End of construction (EOC).

b) Long term steady state seepage (LT).

c) Rapid draw down (RDD).

d) Earthquake loading. (EQ).

Ground improvement is recommended if the EQ factor of safety (FS) > 1.0 and the following conditions are met.

EOC (FS) <1.3

LT (FS) <1.5

RDD (FS) < 1.0.

Bearing capacity and settlement analysis are based on static and dynamic loading conditions. If the factor of safety for bearing capacity is less than required and the settlement estimates exceed allowable, then ground improvement may be recommended.

Seepage estimates are determined in terms of seepage factors of safety by analyzing seepage quantity, uplift pressure and factor of safety against erosion and piping. Ground improvement may be necessary if seepage quantity exceeds allowable, and the uplift pressure is greater than allowable in addition to the factor of safety against erosion and piping being less than required.

Gross ground deformation estimates due to liquefaction is obtained by:

a) Evaluation of bearing capacity safety factor (F_{bc}) considering porewater pressure estimates.

b) Estimation of settlement.

c) Estimates of lateral deformation.

From these analysis, ground improvement is recommended if $F_{bc} < 0.8$ and/or lateral deformation $>2D_{h.a}$ and settlement $>2D_{v.a.}$

5.6.3 Improvement Method Selection

This area is the most critical aspect of ground improvement technology and forms the major area of concern of this research. The choice of a suitable method for any particular situation is made depending on the site soil conditions, the loads to be applied in addition to a host of other factors. The experts make decisions by use of empirical knowledge and estimating the performance of the structure to be built in terms of safety and serviceability.

In order to obtain the views of domain experts relating to the different ground improvement methods, it was decided that questions relating to this area be of the open question format, however, taking cognizance of the fact that the answers to such questions are often difficult to analyze. In the initial stages of conducting the interviews, the interviewees were asked to freely "think-aloud" on the subject of ground improvement method selection. For instance, *'Which factors play a role in ground improvement method selection'? Given a certain site condition, how is this condition assessed and what is its influence on the improvement method selection decision-making?* By this approach, it was envisaged that the reasons for using ground improvement approach for solving certain foundation problems and the factors that initially came to the expert's mind in deciding to use a particular ground improvement method could be identified. In addition, an idea can be obtained on how the factors are interpreted and the evaluation criteria employed. To illustrate this further, assuming an interviewee indicated that a site factor such as 'site accessibility' is important in selecting the dynamic compaction method, it is crucial to probe further to know if the interviewee is referring to site accessibility in general, or site accessibility in respect to the supply of materials, the transportation of installation equipment or even the movement of the work force to and from the site. Again if the interviewee considers groundwater as another important site factor in the selection of the dynamic compaction method, questions arise as to if it is high water table or low water table that is being referred to or the saturation levels of the soil that is of much concern.

In view of the foregoing, a matching process by means of decision tables was adopted in order to appropriately represent the decision-making process. Wets (1998) describes a decision table (DT) as a tabular representation that displays the possible actions that a decision-maker can follow according to the outcome of a number of relevant conditions and one that describes and analyses procedural decision situations where the state of a number of conditions jointly determines the execution of a set of actions. According to Witlox (2002), the tabular representation of the situation is characterized by the separation between conditions and actions, on one hand and between subjects and conditional expressions (states) on the other. Each column in the table (decision column) is indicative of the actions that should (or should not) be executed for a specific combination of conditions of states. Witlox (2002) used this matching procedure in "Matching Algorithm, A Technique for Industrial Site Selection and Evaluation" (MATISSE) to represent the matching results as disjunct sets of conjoint conditional statements that can be thought of as a group of if-then rules.

A generic relational approach by means of a DT is shown in Table 5.26.

Matching result	
C_1 Improvement method factor 1 C_2 Improvement method factor 2 . . C_n Improvement method factor n A_1 Match evaluation	Condition states C_1 Condition states C_2 . . Condition states C_n Action state A_1

Table 5.26: A Generic Relational Approach by Means of a DT (modified after Witlox, 2002).

From Table 5.26 a generic decision rule may be written as:

IF condition state of C_1 (implying improvement method factor 1)

AND

condition state of C_2 (implying improvement method factor 2)

.

.

AND

condition state of C_n (implying improvement method factor n)

THEN

Action state of A_1 (indicating a matching outcome or rule)

As noted in Chapter 2, there are numerous ground improvement methods available. The use of any one method by a particular expert or group of experts may range from technical know how through economic considerations to availability of equipment or materials. Some of the methods are more commonly used than others. Figure 5.2 illustrates the groups of methods that are used by most of the respondents. The densification techniques and reinforcement methods appear to be the methods that are common among the respondents. The thermal treatment methods are the least used. There is no indication of the use of the electro treatment methods by any of the participants.

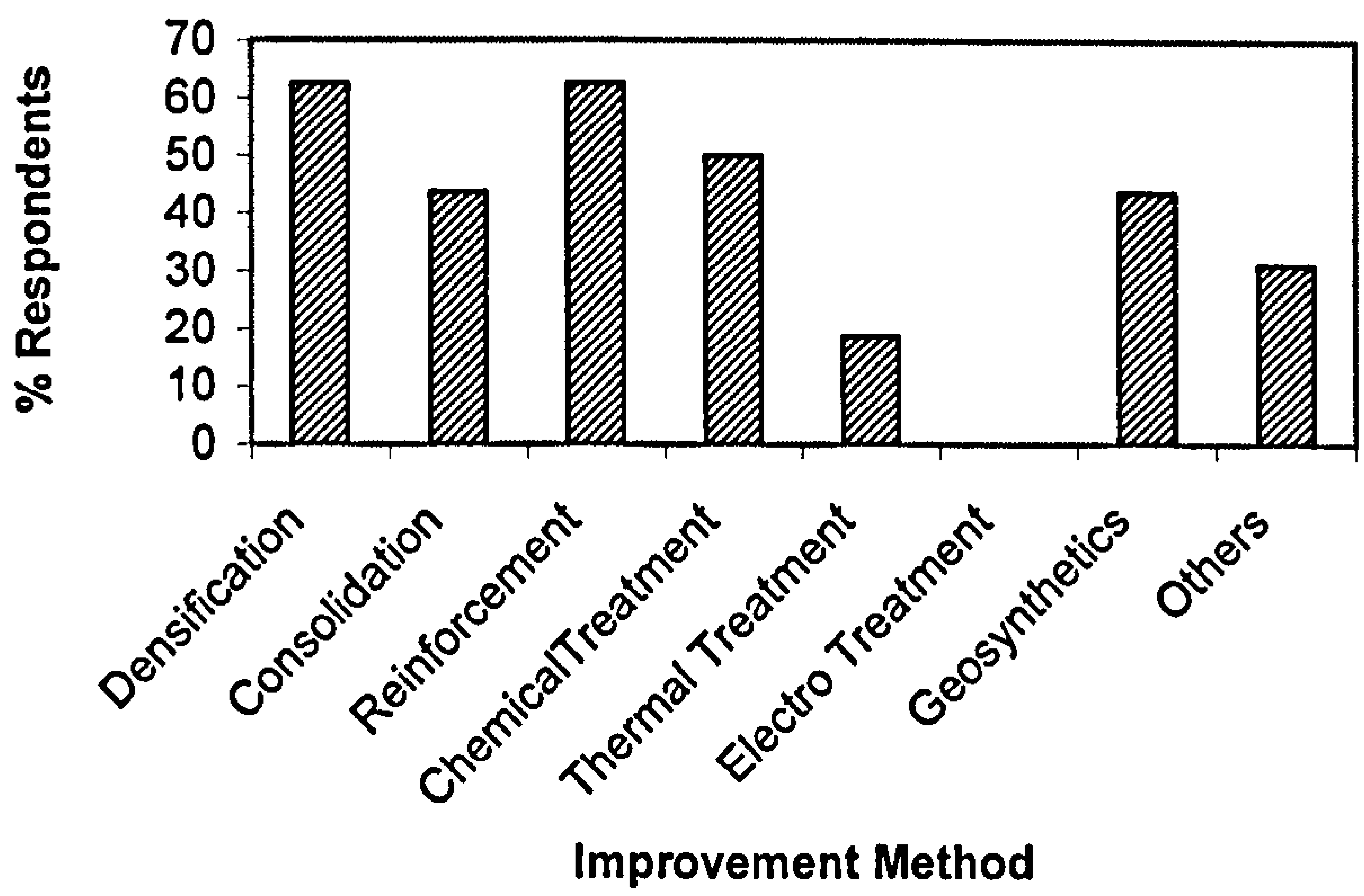

Figure 5.2: Ground Improvement Method Usage

On the individual methods basis, the most common ground improvement methods that the respondents have used are dynamic compaction, lime and stone columns and the vibratory techniques such as vibrocompaction and vibro replacement (Appendix C). Reinforcement methods such as soil and rock anchors and soil nailing are also popular among the respondents. More than 50% of the respondents have used these techniques or are conversant with their applications. Fewer than 50% of the respondents have used the preloading or surcharge techniques and geosynthetics. Methods such as electro-heating, electro-osmosis and natural reinforcement are the least popular or seldom used by any of the respondents. Most of the methods that are frequently used are intended to either densify the soil for bearing capacity increase or to control settlement. The majority of the respondents (75.5%) are based in the UK as a result no regional trends could be observed from the returned questionnaire.

The diversity in the above values as regards the application of the methods may be attributed to several factors including feasibility of alternative methods, equipment availability, lack of technical know-how of the method, cost, the type of facilities that these methods may be applicable to and also tradition. To illustrate a few of these factors, the deep mixing methods commonly used in Southeast Asia (particularly Japan) for marine projects, has a long traditional association. In Sweden and Finland these methods have been used for land projects on soft clays. It is also worth noting that for innovative methods such as Calcite In-situ Precipitation Systems (CIPS) and dry deep mixing technique, only the developers use them.

Indeed, these figures may not actually reflect the popularity of the methods among many ground improvement consultants worldwide due to the limited number of responses, however, the reasons that have been assigned to the use of each method may not vary significantly in terms of worldwide usage. Van Impe et al (1997a) have shown the following methods to be the ones most regularly used in Belgium (Table 5.27).

Traditional Improvement Methods	Ground Reinforcement Methods	Ground Treatment Methods
Vibrocompaction Drainage techniques Stone Columns Lime Columns	Geosynthetics Anchorages Soil Nails Pinpiles Diaphragm walls	Jet Grouting Slabjacking Shallow Soil Mixing.

Table 5.27: Most Regularly used Ground Improvement Techniques in Belgium (after Van Impe et al, 1997a)

Following responses from the various domain experts together with abstracted information from the literature (e.g. Munfakh and Wylie, 2000) the conditions that are considered most critical in the selection of a method are categorized into the following broad areas.

a) Ground conditions
b) Facility type
c) Construction related considerations
d) Site conditions
e) Economic considerations
f) Environmental factors
g) Miscellaneous considerations

Under each of these are a number of sub-conditions. For example site conditions is further specified by sub-conditions such as site restraint due to development, site accessibility, availability of headroom, proximity of structures, presence of utilities (buried or surface), site size and whether site is open or confined. Similarly, ground conditions is also specified by other sub-conditions such as soil type, groundwater condition, permeability, stratification, uniformity of formation, layer thickness. The details are discussed in Chapter 6. It is however necessary to state that although most of these parameters are very important in the method selection process it is difficult to quantify them owing to the manner in which the results are presented.

Descriptive terms such as poor, good, inferior, superior, favourable, unfavourable, high low, medium, important, unimportant, heavy, moderate, light and many more have been used to assess the attributes. For example site-condition ***poor*** may be used as an assessment of a site with site restraints such as buried utilities. It is also used to represent a site with low or no headroom so that the selection of a particular ground improvement method for example dynamic compaction will depend on how the conditions interact with each other. Table 5.28 is a decision table for ground improvement based on the above grouping of the applicable conditions for low moderate and high environmental effect. Load due to the type of facility is considered as heavy, however three condition states heavy, moderate and light have been distinguished and the decision tables are shown in Appendix D.

Ground conditions

The effectiveness of an improvement technique pivots around the nature of the ground. Ground conditions relate to knowledge about the physical, mechanical and chemical properties of the subsurface materials at the site under consideration. The engineering characteristics of the underlying soil are very important for the design of any ground improvement technique.

The respondents have listed several ground condition related parameters. These geotechnical parameters that are invaluable in the selection of a technique include grain size distribution, soil density, consistency, activity, soil strength, permeability, compressibility, sensitivity, water content, clay content and the chemical constituents such as organic content and sulphate content. Where these parameter values are below the expected value the ground condition is designated as 'poor'. Each one of these

<table>
<tr><td>facility load</td><td colspan="12">heavy</td><td colspan="12">heavy</td><td colspan="12">heavy</td></tr>
<tr><td>ground-condition</td><td colspan="12">poor</td><td colspan="12">poor</td><td colspan="12">poor</td></tr>
<tr><td>site-condition</td><td colspan="12">poor</td><td colspan="12">poor</td><td colspan="12">poor</td></tr>
<tr><td>economic-considerations</td><td colspan="12">low</td><td colspan="12">low</td><td colspan="12">low</td></tr>
<tr><td>environmental-impact</td><td colspan="12">low</td><td colspan="12">moderate</td><td colspan="12">high</td></tr>
<tr><td>expertise</td><td colspan="6">high</td><td colspan="6">low</td><td colspan="6">high</td><td colspan="6">low</td><td colspan="6">high</td><td colspan="6">low</td></tr>
<tr><td>construction-related-issues</td><td colspan="3">important</td><td colspan="3">unimportant</td><td colspan="3">important</td><td colspan="3">unimportant</td><td colspan="3">important</td><td colspan="3">unimportant</td><td colspan="3">important</td><td colspan="3">unimportant</td><td colspan="3">important</td><td colspan="3">unimportant</td><td colspan="3">important</td><td colspan="3">unimportant</td></tr>
<tr><td>miscellaneous</td><td>L</td><td>M</td><td>H</td><td>L</td><td>M</td><td>H</td><td>L</td><td>M</td><td>H</td><td>L</td><td>M</td><td>H</td><td>L</td><td>M</td><td>H</td><td>L</td><td>M</td><td>H</td><td>L</td><td>M</td><td>H</td><td>L</td><td>M</td><td>H</td><td>L</td><td>M</td><td>H</td><td>L</td><td>M</td><td>H</td><td>L</td><td>M</td><td>H</td><td>L</td><td>M</td><td>H</td></tr>
<tr><td>methods
(soil type dependent)</td><td colspan="12">preloading, vacuum consolidation, vibro techniques
dynamic compaction</td><td colspan="12">lime/cement stabilization, lime columns,
drainage</td><td colspan="12">jet grouting, compaction grouting,
reinforcement methods</td></tr>
</table>

Notes: L= low M = Moderate H = High

<table>
<tr><td>facility load</td><td colspan="12">heavy</td><td colspan="12">heavy</td><td colspan="12">heavy</td></tr>
<tr><td>ground-condition</td><td colspan="12">poor</td><td colspan="12">poor</td><td colspan="12">poor</td></tr>
<tr><td>site-condition</td><td colspan="12">poor</td><td colspan="12">poor</td><td colspan="12">poor</td></tr>
<tr><td>economic-considerations</td><td colspan="12">moderate</td><td colspan="12">moderate</td><td colspan="12">moderate</td></tr>
<tr><td>environmental-impact</td><td colspan="12">low</td><td colspan="12">moderate</td><td colspan="12">high</td></tr>
<tr><td>expertise</td><td colspan="6">high</td><td colspan="6">low</td><td colspan="6">high</td><td colspan="6">low</td><td colspan="6">high</td><td colspan="6">low</td></tr>
<tr><td>construction-related-issues</td><td colspan="3">important</td><td colspan="3">unimportant</td><td colspan="3">important</td><td colspan="3">unimportant</td><td colspan="3">important</td><td colspan="3">unimportant</td><td colspan="3">important</td><td colspan="3">unimportant</td><td colspan="3">important</td><td colspan="3">unimportant</td><td colspan="3">important</td><td colspan="3">unimportant</td></tr>
<tr><td>miscellaneous</td><td>L</td><td>M</td><td>H</td><td>L</td><td>M</td><td>H</td><td>L</td><td>M</td><td>H</td><td>L</td><td>M</td><td>H</td><td>L</td><td>M</td><td>H</td><td>L</td><td>M</td><td>H</td><td>L</td><td>M</td><td>H</td><td>L</td><td>M</td><td>H</td><td>L</td><td>M</td><td>H</td><td>L</td><td>M</td><td>H</td><td>L</td><td>M</td><td>H</td><td>L</td><td>M</td><td>H</td></tr>
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drainage</td><td colspan="12">jet grouting, compaction grouting
reinforcement methods</td></tr>
</table>

Notes: L= low M = Moderate H = High

TABLE 5.28 : Decision Table for Ground Improvement Method Selection (Load: Heavy)

parameters may have the same significance as others depending on the type of soil under consideration when considering the use of a particular ground improvement method.

The influence of any parameter on the choice of the method to be selected can be assessed by the use of simple decision tables. Table 5.29 is a decision table for some of the sub-conditions of ground conditions.

Soil density	loose								dense
Stratum thickness	thin				thick				
Stratum depth	shallow		deep		shallow		deep		
groundwater	low	high	low	high	low	high	low	high	
Shallow densification	+	+	+		+				Do nothing
Deep densification			+	+		+	+	+	
Dewatering		+		+		+	+	+	

Table 5.29: Decision Table for Ground Conditions

Four conditions namely: soil density, stratum thickness, stratum depth and groundwater have been used to evaluate the attribute 'ground conditions'. The table exhibits how the condition states interact with each other for the selection of an appropriate technique of ground improvement for loose soil. When the condition 'soil density' is evaluated as dense, there is no improvement method suggested indicating such a soil does not require improvement. Since the soil is dense, it will have low voids ratio and porosity thus rendering it impervious to groundwater. Thus groundwater will possibly not have any adverse effect on such a material. Each of these sub-conditions can take on more than one possible state. For example, 'stratum thickness' can be either 'thin' or 'thick'.

There are several ground conditions that need to be considered if ground improvement is to be suggested. Only a few are indicated in Table 5.29 for illustrative purposes. Figure 5.3 illustrates the influence of grain size on the application of some of the methods. Most methods are applicable over a wide range of soil types whereas others can be applied to only a type or limited range of soils. The proportion of the various soil fractions in a soil mass therefore plays an important role in the performance level and or applicability of a method. To illustrate this fact, whereas the following ground improvement techniques namely, dynamic compaction, vibrocompaction and blasting can all be employed in order to densify loose granular soil, the vibrocompaction method is particularly suited for clean sands with silt content generally less than 12 to 15% with or without clay content less than 3%. The dynamic compaction method can be used for a wider range of soils including cohesive soils whiles the blasting method is applied only to loose granular soils above and below the water table.

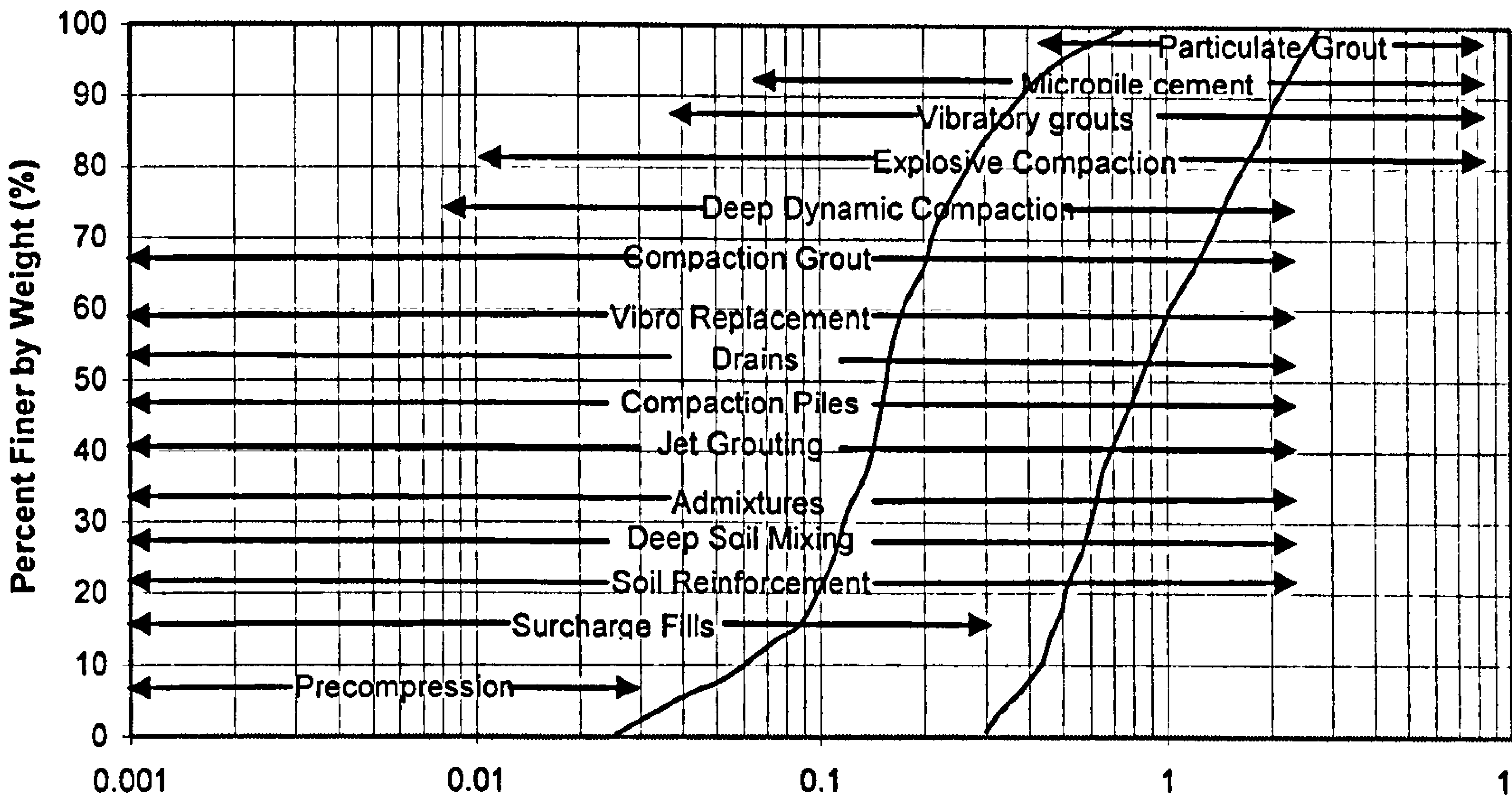

Figure 5.3 : Applicable Grain Size Range for Soil Improvement Methods (Modified After Department of The Army, 1999)

In general, the engineering characteristics of the soil determine in the first instance the type and performance of the improvement methodology whether as a means of increasing bearing capacity, reduction of settlement to acceptable levels, stabilization purposes, remediation of liquefaction, or even to serve as seepage cut-off. Where soil density is a suspect, the most suitable methods to use are those that will result in densifying the soil to a desirable level. Compressible soils undergo settlement when they are subjected to load from a structure or may heave following any reduction in the loading condition. In such situations the most appropriate methods to use are those that will prevent or minimize settlement or heave.

Apart from the soil characteristics, other ground condition related factors include the geology of the site in terms of stratigraphic relations, thickness of the various strata or stratum and variability of formation. Where very thick soil formations are encountered, the selection of the method may be determined by the maximum depth to which a method can improve the quality of the poor soil formation. In situations where variable soil formations may exist laterally, more than one method of improvement has been recommended in order to cover all the soil formation within the footprint of the proposed structure.

All the participants have indicated groundwater as one of the top priority parameters that determine the choice of a method. On a rating of 0 - 100% on the role of groundwater in the ground improvement method selection process all have placed groundwater in the top 80-100%. Therefore groundwater was included as one of the top sub-conditions of the ground conditions.

Construction Related Issues

The several parameters that have been listed and grouped under this caption are shown in Table 5.30. It is generally agreed that construction schedule plays a significant role in the method selection process. Where time is not a problem, participants have recommended the use of cost effective methods such as preloading which may take a long time to produce similar effects as with costly methods. However this depends on the type of soil to be improved and other factors such as the thickness of formation.

Factor	Parameter
construction-related-issues	Schedule Maintenance-requirements Material-durability Materials-availability Labour-considerations Equipment-availability

Table 5.30: Construction Consideration Parameters.

When foreign materials have to be introduced to improve the soil quality, then issues such as material availability and material durability have been considered as important factors. The use of methods like the preloading and surcharge techniques require the use of fill material. As a result participants recommend the use of such methods only when there is economic haulage distance of under 15km.

In addition to the above labour issues is also considered to be an important parameter in the method selection process. Though difficult to quantify this plays an important role where strong labour laws are operative and particularly significant where labour intensive methods are under consideration.

Environmental Concerns

One of the factors that play a key role in the selection of a ground improvement methodology is the impact the use of the method will have on the environment. Important parameters that need to be addressed include the noise levels that will be encountered in the process of installing a method particularly in inhabited areas. Noise level above 85dB is considered undesirable to human beings. In situations where the site under consideration is contaminated with hazardous materials or waste, the use of methods that will involve the discharge of considerable volumes of water (e.g. jet grouting, vibro-replacement) is limited. Excessive ground vibrations that may occur during the installation of some methods such as dynamic compaction could also have damaging effects on adjacent structures or could even result in minor land slides in uneven topography underlain by weak materials. In addition to the above, consideration is also given to effects the use of a method will have on the aesthetic value of the site.

Site Conditions

Existing site conditions play a significant role in the decision making process. The site conditions that have been regarded as important include:

a) Surface topography.
b) Unstable working surface.
c) Site accessibility.
d) Site constraints such as surface or subsurface utility structures.
e) Headroom: important in situations where installation equipment may require sufficient overhead clearance.

Topography and site accessibility are cited as important factors when heavy equipment have to be transported to the site under consideration. Sufficient headroom is also cited as an important factor when considering methods such as the installation of vertical drains. Where heavy equipment is to be used on soft or weak ground a stable working surface has been recommended.

Economic Considerations

The decision to use any method or a combination of methods for any particular situation will depend finally on cost. Though not all the questionnaire respondents agree that cost plays a significant role, all the experts interviewed agree on the importance of cost as a deciding factor as the various methods vary in terms of cost of implementation depending on size and extent of the project.

Miscellaneous Considerations

Several other factors that are important in the decision making process have been cited by the experts. The most important factors that have been listed include, politics, traditions, availability of expertise, labour skills, and trade limitations (Table 5.31). There is very limited agreement among the experts on the importance of some of these factors in the decision making process. For example, most respondents do not see politics as a factor relevant for the selection of a method even though this has been cited in the literature. Munfakh (1997) has indicated the influence of politics on the selection of the deep vibrocompaction technique for the densification of sand backfill behind a deteriorated wharf at Kismayo Port, Somalia. Politics also played a role in the selection of the preloading technique for the densification of interlayered alluvium sand and silty clay deposits that underlie the site for the construction of a fuel tank farm and distribution system for the Chek Lap Kok International Airport, Hong Kong. An issue such as tradition however has been considered to be important since most local contractors may be associated with some traditional practices based on the labour skill levels and also equipment availability. Methods that are patented to some firms may probably never be considered feasible in order to avoid legal issues.

Factor	Parameter
Miscellaneous consideration	Politics Traditions Contractual issues Expertise Skilled labour Trade limitations

Table 5.31: Miscellaneous Consideration Parameters

5.7 Conclusions

The various criteria used in the identification of problem soils have been discussed. Several parameters and correlation charts have been used for the identification of these soils however the most widely used format of presenting the soil properties is in terms of intervals. These intervals vary considerably from one researcher to the other. The most fundamental argument for such differences is levelled on imperfections in both laboratory and field tests and differences in the standards of testing in the various regional set ups or countries. Furthermore it sounds unrealistic to suppose that even at a point location all the soil properties can be determined with precision. The soil properties are site specific and variations are bound to occur locally and remarkably over regions remote from each other.

The selection of a ground improvement methodology for a construction site is based on several factors the primary reason being the presence of problem soils. Decision tables have been used to properly represent the selection procedure.

CHAPTER 6

IMPLEMENTATION OF GROUND IMPROVEMENT TECHNOLOGIES IN CLIPS

6.1 Introduction

A number of uncertainties are associated with ground improvement technologies. As a consequence, before any of the numerous traditional methods is applied in a particular situation either singly, or in combination with other methods, to solve a foundation problem, field trials are almost always resorted to in order to ascertain the suitability of the proposed technique(s). These trials are often carried out with the view to assisting the geotechnical engineer in choosing the most appropriate method.

Even then the use of any particular method depends on a number of uncertainties and several considerations come into play in the decision to apply a ground improvement methodology. The use of some form of assistance is seen as a boost to the performance of the engineer and is also envisaged to save his time. To date, few such assistants for ground improvement are known.

This chapter deals with the building of a knowledge-based system for ground improvement method selection (GrIMSA : **G**round **I**mprovement **M**ethod **S**election **A**ssistant) with the primary aim of serving as a decision support tool for the geotechnical engineer to select the most appropriate method for the improvement of a problematic soil on which a civil engineering facility is to be cited.

The chapter begins by describing in Section 6.1 the general CLIPS development environment. In Section 6.2 the knowledge representation and construction of two knowledge bases that were found to appropriately represent the information gathered from the knowledge acquisition process is discussed.

In Section 6.3, a general discussion of certainty factors introduced in the method selection knowledge-based system to account for uncertainty in the criteria used for the selection of each method is presented. This is followed by a discussion in Sections 6.4 and 6.5 on how wxCLIPS handles uncertainty by the use of certainty factors to demonstrate the measure of believe that the expert has in the suitability of the selected method(s) after the user provides input data to the rules.

The conclusions drawn from this chapter are presented in Section 6.6.

6.2 The CLIPS Development Environment

As indicated in Section 5.3, the expert system shell selected for this research work is wxCLIPS version 1.64 which is a variant of NASA's CLIPS expert system shell. The CLIPS expert system can be executed in three ways namely: interactively using a simple text-oriented command prompt interface; interactively using a window/menu/mouse interface on certain machines; or as embedded expert systems in which the user provides a main program and controls execution of the expert system.

The generic CLIPS interface consists of a simple, interactive, text-oriented command prompt interface for high portability. A knowledge base is created by the use of any standard text editor. This is then saved as a text file, which can be loaded into CLIPS.

CLIPS uses both heuristics and procedural paradigms for representing knowledge (Giarratano and Riley, 1998).

Heuristic knowledge is represented in the form of rules, which specify sets of actions to be performed for a given situation. A **rule** consists of an **antecedent** and a **consequent.** The antecedent of a rule is a set of conditions (or conditional elements) that will have to be satisfied for the rule to be applicable. This is accomplished by the existence or non-existence of specified facts in the specified fact-list or specified instances of user-defined classes in the instance-list. The consequent of a rule on the other hand is the set of actions to be taken when the rule is applicable and this happens only when the CLIPS inference engine is instructed to begin the execution of applicable rules. The inference engine always keeps track of rules that have their conditions satisfied and thus rules can immediately be executed when they are applicable.

In the case of the procedural paradigm, CLIPS uses **deffunctions** and **generic functions** to allow the user to define new executable elements that perform a useful side effect or return a useful value. A **deffunctions** is one of several defining constructs in CLIPS. It allows the definition of new functions in CLIPS directly using CLIPS syntax. **Generic**

functions consist of two types of constructs namely **defgeneric** construct and **defmethod.** The **defgeneric** construct specifies the generic function header and the **defmethod** construct represents the multiple components where each method handles different cases of arguments for the generic function. If a generic function has more than one method, it is said to be overloaded.

6.3 Knowledge Representation

In the construction industry the decision to use ground improvement construction technology to improve the quality of subsurface materials at a proposed site for a facility depends on several considerations. The initial steps in the decision process usually involve the identification of the type(s) of soil that underlie the potential site after the type of facility is defined. This is normally achieved by conducting a site investigation to determine the soil or ground characteristics. Thorough analysis of the site investigation data is then carried out to determine if ground improvement methodology is necessary and whether this is the most appropriate approach in comparison with other construction alternatives such as piles, piers or caissons or even recommendation for a total or partial removal of any underlying problematic soil. If ground improvement is the most suitable construction alternative, the problem then narrows down to selecting the most appropriate method from several ground improvement techniques by considering the several conditions cited by the experts.

Ground improvement can be performed on soil or rock deposits at both shallow and deep depths. A decision tree developed for the acquired knowledge in relation to the methods that are usually employed is shown in Figure 6.1. Two broad groups of ground improvement methods are distinguished namely: shallow ground improvement techniques and deep ground improvement techniques. Shallow ground improvement techniques are applicable to formations at shallow depths while the deep improvement techniques are most suitable when the improvement needs to be carried out to or conducted at great depths. This division has been found necessary because some ground improvement techniques, by their mode of application and or performance levels, have depth limitations. For example, the biotechnical technique can be used to strengthen weak or loose soil masses through the binding together of the soil grains as a result of biotechnical processes relating to the soil-plant root system. Many plants apart from those with a taproot system however, have their roots close to the ground surface.

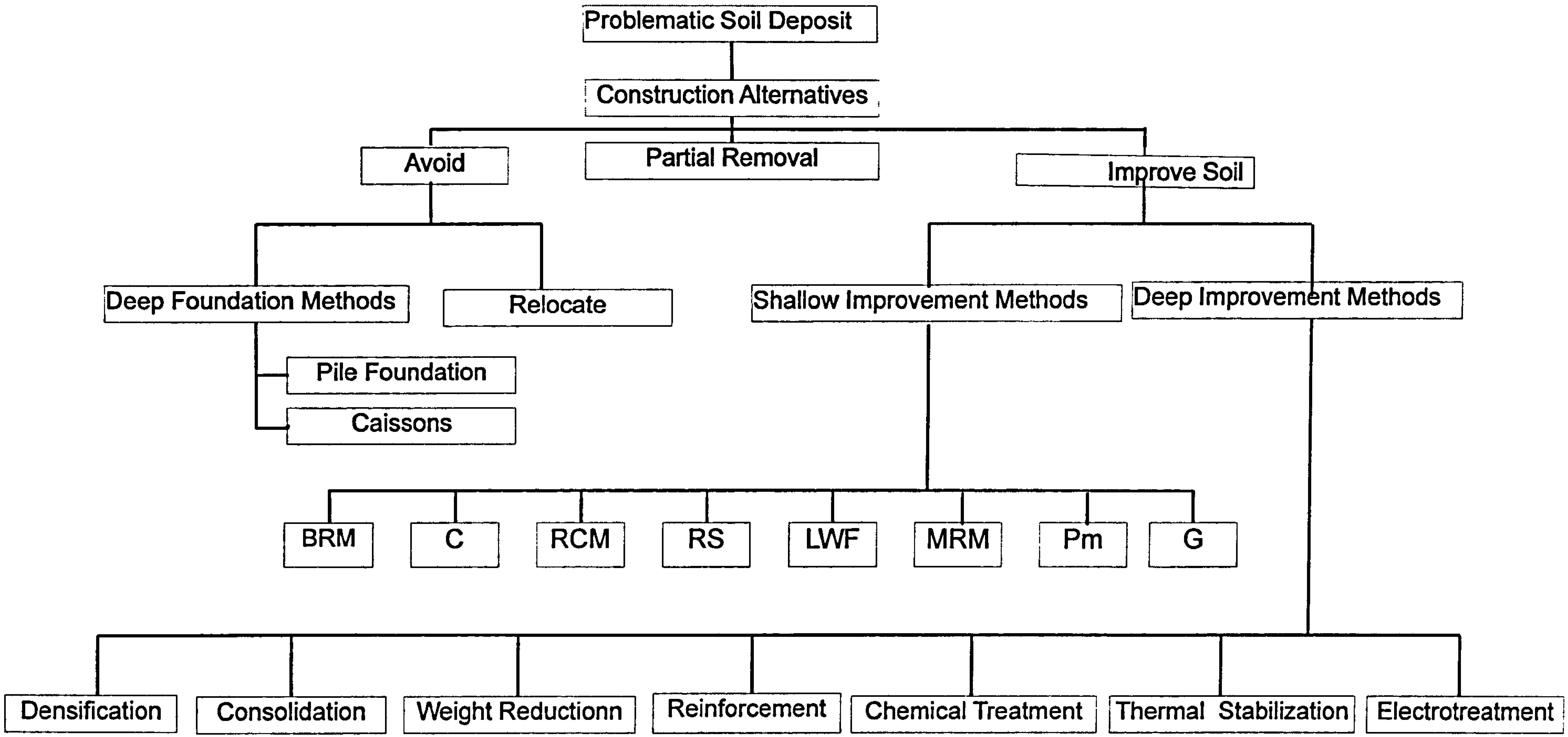

Figure 6.1: Ground Improvement Decision Tree

LEGEND

BRM =Blasting Replacement Method
C = Cement &/or Lime Stabilization
RCM = Roller Compacted Method
MRM = Mechanical Replacement Method
LWF = Light Weight Fill
RS = Replace Soil
Pm = Pre-mix Soil
G = Geotextile

Consequently, the biotechnical techniques can be used for the improvement of soil at shallow depths only.

The deep ground improvement techniques shown in the diagram represent groups of techniques comprising a number of techniques (to be shown later in Subsection 6.2.3), which are either similar in the method of application or the purpose for which they are used. For instance, the densification technique group comprises the following: vibrocompaction, dynamic compaction, blasting and compaction grouting. All these methods serve the purpose of densifying loose granular soils. However, the choice of any one of them may be dependent on a number of other factors. The vibrocompaction method for example, is more suited for clean sands with silt contents generally less than 12 to 15% and or clay content less than 3% (ASCE, 1997), whereas the blasting technique maybe most appropriate in situations where obstructions such as boulders and large wood debris in the deposits may pose high risks of damaging the equipment used in the installation of the other three methods.

If analysis indicates adverse settlement conditions are likely to occur, the most appropriate choice of method(s) should be from the consolidation techniques group to speed up the rate of consolidation of the soil thereby improving the ground settlement.

The chemical treatment group comprises methods which use chemical constituents for the improvement of the problematic soil. The reinforcement group consists of construction methods which involve the introduction of materials such as geosynthetics or metal rods into the soil. These methods by themselves do not necessarily improve the properties of the soil but are used for reinforcement in order to absorb some of the load from the structure.

This grouping is by no means rigid as it is possible that some of the methods can be used to accomplish more than one purpose, say densification and settlement. There are overlaps of many methods and groups shown in the figure above. It is possible that a method classified as a reinforcement method for example the stone columns method can also be used for settlement control.

In the event that the poor soil formation occurs at very shallow depth it may be more convenient and economical to completely or partially remove it and then replace with a more competent material. The improvement of the properties of a problematic soil deposit occurring at shallow depths can be conducted by techniques such as cement and or lime stabilization, lightweight fill and others shown in the figure.

With a suitable amount of knowledge gathered in relation to the conditions under which each method can be successfully applied, the structure and representation of the knowledge-based system could be determined. As noted in Section 5.6, two distinctive areas of consideration are important in the decision making process when considering the use of ground improvement technology. These areas are:

a) The preliminary evaluation process
b) The ground improvement method selection.

In order that the knowledge collected was adequately represented, it was deemed necessary to represent these two as separate and distinct components.

The preliminary evaluation process comprises two essential components namely;

a) Problematic soil characterization process
b) Evaluation to identify the need for ground improvement

The problematic soil characterization process precedes the evaluation to identify the need for ground improvement. Series of rules relating to each of the above components were then established separately to form two knowledge bases namely:

a) Soil characterization and ground evaluation knowledge-base
b) Ground improvement method selection knowledge-base

6.3.1 The Soil Characterization and Ground Evaluation Knowledge Base

This contains rules that use facts related to the soil characteristics that identify the type of problematic soil. As noted in Chapter 5, site characterization is an essential component of any geotechnical site investigation. In all areas where problematic soil may be found, the tests normally conducted may range from classification and index tests to consolidation and triaxial tests. An adequate interpretation of the results from such an investigation provides the engineer with the necessary data for any alterations that may be necessary in the design of the structure to be established, or guidance about any modifications of the properties of the subsurface materials for the successful implementation of the proposed project.

The soil characterization and ground evaluation knowledge base contains rule sets that are designed to identify 15 soil types based on the Unified Soil Classification System (USCS). Since ground improvement is resorted to only when unsuitable subsurface conditions exist at a site, the soil characterization and ground evaluation knowledge base further contains rule sets that are designed to produce outputs on the main soil types, which are classified as problematic in the geotechnical literature as discussed in Subsection 5.6.1. The rules have been formulated based on the characteristics of these soils with the view to identifying individual layers of such soils that may form part of the substratum material.

In addition to the soil characteristics, the location of the site, the depth of occurrence and thickness of formation have also been included in order that the engineer knows exactly at what levels the poor soil condition exists and what thickness of poor soil stratum needs to be improved. At this level, data on the depth and thickness of formation are used to evaluate the need for ground improvement and also to be used at a later stage by the engineer for the following purposes:

a) choice of ground improvement methodology and
b) estimation of cost of improvement technique.

On completion of this section the user is given an indication of the type of problem soil at the specified depth and location and an advice as to whether ground improvement is necessary after providing input data to the rules relating to the soil types.

In order to formulate good rule sets for the identification of problematic soils, the following conditions were considered necessary.

The rule set should:

a) never result in an impossible conclusion;
b) encompass all possible outcomes.

The rules were formulated based on the soil characteristics using existing data from the literature as the starting point in the development of the decision support system. The soil characteristics used include:

a) Soil index properties
   - dominant grain size range
   - density (bulk, dry and relative density)
   - Atterberg limits (w_L, w_P, I_P)
   - indices from correlation charts
      i. Expansion index
      ii. Collapse potential
      iii. Liquefaction potential
   - sensitivity
   - frost susceptibility

b) Strength parameters
   - cohesion (c)
   - friction properties (Ø)
   - bearing capacity (q)

c) Composition
   - clay mineralogy
   - organic matter content
   - fibre content
   - ash content

d) Compressibility
   - coefficient of consolidation, c_v
   - coefficient of volume change, m_v

e) Permeability (hydraulic conductivity, k.)

f) Soil structure

Soil grain size distribution is one important property that is used to classify soils into four major divisions namely, granular (or coarse-grained) soils, non-granular (or fine-grained) soils, organic soils and peat. According to the Unified Soil Classification System, USCS, (Table 6.1), non-granular soils (fine-grained soils) have at least 50% of their grain size passing the #200 sieve. Conversely, granular soils are characterized by having less than 50% of their grain size passing the #200 sieve.

Major Division	Grain Size Distribution	Group Symbol	Soil Description
Coarse- grained material (more than 50% of material is larger than No.200 sieve size)	Gravel and gravely soils 50% or more of coarse fraction larger than No. 4 sieve size	GW	Well-graded gravels, gravel-sand mixtures, little or no fines (clean gravels; less than 5% fines)
		GP	Poorly-graded gravels, gravel-sand mixtures, little or no fines (clean gravels; less than 5% fines)
		GM	Silty gravels, gravel-sand-silt mixtures (gravels with more than 12% fines)
		GC	Silty gravels, gravel-sand-clay mixtures (gravels with more than 12% fines)
	Sands 50% or more of coarse fraction smaller than No. 4 sieve size	SW	Well-graded sands, gravely sands, little or no fines. (Clean sands; less than 5% fines)
		SP	Poorly-graded sands, gravely sands, little or no fines. (Clean sands; less than 5% fines)
		SM	Silty sands, sand-silt mixtures. (sands with more than 12% fines)
		SC	Clayey sands, sand-clay mixtures. (sands with more than 12% fines)
Fine-grained material (50% or more of material is smaller than No.200 sieve size)	Silts and clays Liquid limit less than 50%	ML	Inorganic silts and very fine sands, rock flour, silty or clayey fine sands or clayey silts with slight plasticity
		CL	Inorganic clays of low to medium plasticity, gravely clays, sandy clays, silty clays, lean clays
		OL	Organic silts and organic clays of low plasticity
	Silts and clays Liquid limit 50% or greater	MH	Inorganic silts, micaceous or diatomaceous fine sandy or silty soils, elastic silts
		CH	Inorganic clays of high plasticity, fat clays
		OH	Organic clays of medium to high plasticity, organic silts
Highly organic soils		Pt	Peat and other highly organic soils

Table 6.1: Unified Soil Classification and Symbol Chart.

Symbols such as G (gravel), S (sand), M (silt), C (clay), O (organic) and Pt (peat) are used to represent the major soil grain size. This may be followed by a gradation symbol such as W or P for well-graded and poorly-graded respectively for the description of coarse-grained soils. For example, GP represents poorly graded gravel. When classifying the fine–grained soils the liquid limit (w_L) symbol H representing high plasticity (i.e. if the liquid limit, w_L >50%) or L representing low plasticity (i.e. if liquid limit, w_L <50%) is used based on the associated Casagrande Plasticity Chart (Figure 6.2). Thus CH soils are clays of high plasticity (fat clays), while CL soils are clays of low plasticity (also known as lean clays). Dual symbols such as GM (silty gravel) can also be used. In this case the primary symbol describes the dominant soil grain size and the secondary symbol describes the secondary component.

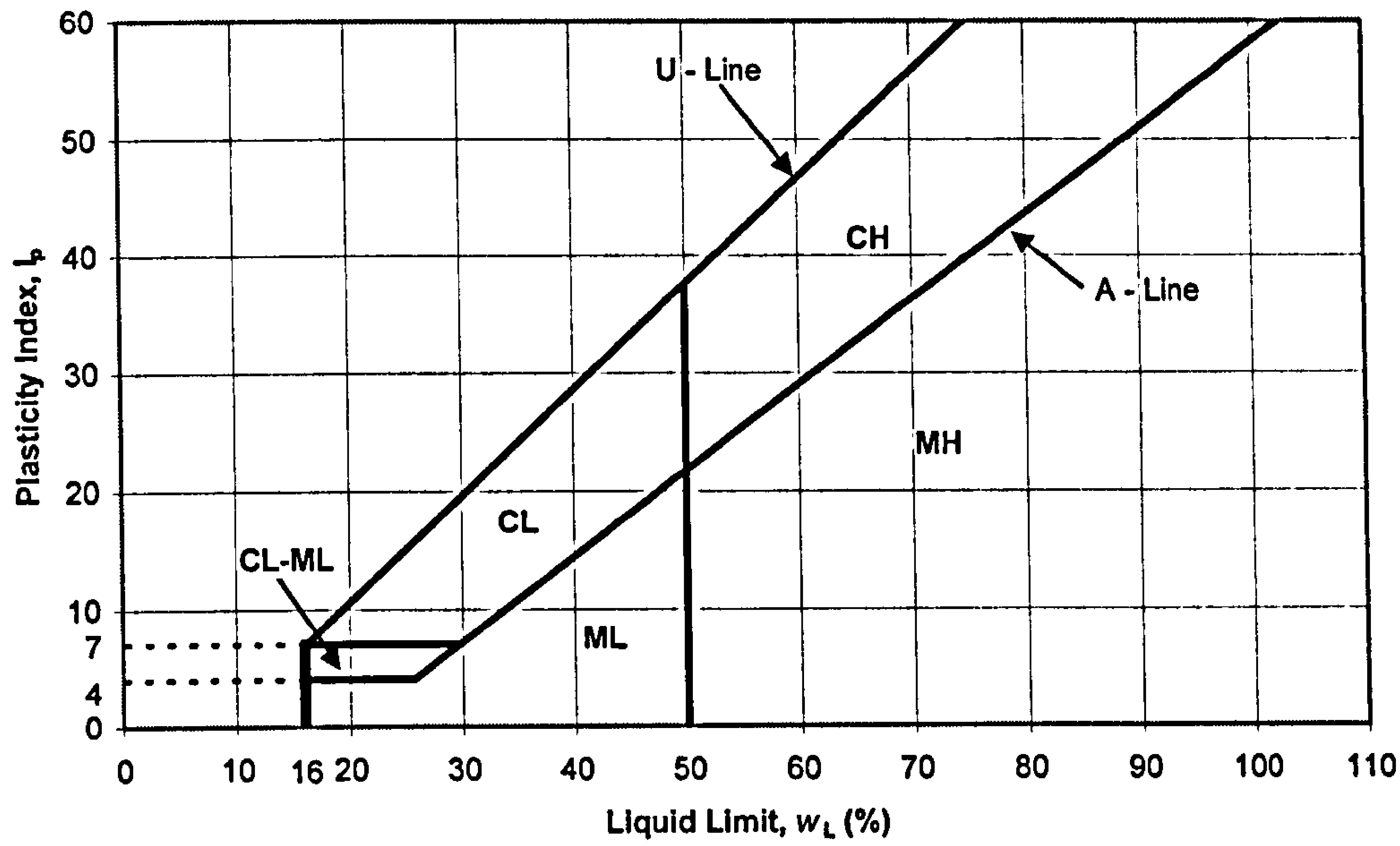

Figure 6.2 : Plasticity Chart (ASTM D2487) for Classification of Fine-Grained Soils

In The British Standard BS 5930 (1981), *Code of practice for site investigations,* soils are classified as either fine soil if at least 35% of the soil can pass through the 63μm sieve or coarse soil if the amount that can pass the 63μm sieve is less than 35%. The main soil types are also designated by symbols as in the USCS. Additional symbols (letters) that are used to further describe the soil and to denote its grading and plasticity are shown in Table 6.2. In this classification system, the group symbol SWM for example is described as well graded silty sand.

Grading		Plasticity		
Symbol	Description	Symbol	Description	Range of value
W	Well graded	L	Low plasticity	$w_L < 35\%$
P	Poorly graded	I	Intermediate	$35 \leq w_L \leq 50$
P_u	Uniform	H	High plasticity	$50 \leq w_L \leq 70$
P_g	Gap graded	V	Very high	$70 \leq w_L \leq 90$
O	Organic	E	Extremely high	$w_L > 90\%$

Table 6.2: Additional Symbols Used in the British Soil Classification System.

Other standards are used by the nationals of different countries around the world. In order to conform to the most common soil classification system among geotechnical engineers, the USCS was adopted for the classification of the soil types.

Most soil classification methods do not classify artificial soils, which have resulted from artificial processes, as a separate soil group. Such soils are mainly fill materials or construction debris, which maybe agglomerations of various soils and industrial waste in addition to rubble from demolished structures often placed in an uncontrolled manner. For the purpose of this research work however this group has been identified as a separate group so as to distinguish such soils from natural soils.

Any of the soils in Table 6.1 may pose problems depending on many factors. For instance silt has lower permeability than sand. The presence of water within a silt deposit has the potential to create instability in silt than in sand by decreasing the internal friction properties of the soil. As a consequence a heavily loaded foundation on this type of soil may lead to a sudden and catastrophic soil failure beneath the foundation. The soil layer may therefore require some improvement. Some soil types are however judged to have excellent engineering characteristics (Table 6.3) and will generally not require any further improvement. The soil under consideration is therefore initially classified into one of these groups using data from a particle size distribution analysis and index tests. Based upon this initial stage of identification the soil is further classified into the specific problem soil type following input data provided by the user in relation to the other soil properties.

Soil group	USCS symbol	Drainage characteristics	Frost heave susceptibility	Compressibility and potential expansion	Bearing capacity (kN/m^2)	Undrained shear strength (kN/m^2)	Ø (degrees)	Value for foundation
Group I Excellent	GW	Good	Low (F1)	Low	129.6-144	NA	38-46	Good
	GP	Good	Low (F1) to Medium (F2)	Low	129.6-144	NA	38-46	Good
	SW	Good	Medium (F2)	Low	38.4-57.6 (loose)	NA	30-46 (loose - dense)	Good
	SP	Good	Medium (F2)	Low	38.4-57.6 (loose)	NA	30-36 (loose - dense	Good to poor depending on density
	GM	Medium	Low (F1) to High (F3)	Low	129.6-144	NA	38-46	Good
	SM	Medium	Medium (F2) to high(F3)	Low	76.8-168 (firm)	NA	28-40 (firm)	Good to poor depending on density
Group II Fair to good	GC	Medium	High(F3)	Low	129.6-144	NA	38-46	Good to poor
	SC	Medium	High (F3)	Low	76.8-168 (firm)	NA	38-34 (dense)	Good
	ML	Medium	Very High (F4)	Low	96	NA	30-34 (dense)	Very poor, susceptible to liquefaction
	CL	Medium	High (F3) to Very high (F4)	Medium	28.8-57.6 (soft) 144-216 (stiff)	0-12 (soft) 48-57.6 (stiff)	NA	Good to poor
Group III Fair to poor	CH	Poor	High (F3)	High to Very high	28.8-57.6 (soft) 144-216 (stiff)	12- 24 (soft) 96-192 (stiff)	NA	Fair to poor
	MH	Poor	Very high (F4)	High	96	76.8	NA	poor
Group IV Unsastisfac-tory	OL	Poor	High (F3)	Medium			-	Fair to poor; possible excessive settlements
	OH	Unsatisfactory	High (F3)	High			-	Very poor
	Pt	Unsatisfactory	High (F3)	High			-	Remove

Table 6.3: The Engineering Properties of Soils.

From the technical literature, the identification of problematic soils is based on a number of characteristics peculiar to each type. Several indices have been derived from the problematic soils characteristics, which form the basis for identification. As outlined earlier in Section 5.6, however, there are no standard or universally accepted limits for the parameters that are used for the identification of a majority of the problem soils. In order to achieve any meaningful results, it was thought appropriate to store the characteristics commonly used by most geotechnical engineers however since regional practices may vary the system can be altered relatively easily to incorporate the systems that are commonly used in each region or country. For example in Sweden, the soils are very soft and often sensitive clays. Therefore the adopted Swedish Standard Code for CPT is rigid and is said to be the hardest in the world. The use of the standard CPT values in this country will result in poor decision.

The following are summaries of the characteristics of the problematic soils that are considered vital in the building of the soil characterization and ground evaluation knowledge base and which therefore have been stored in this knowledge base. The details of the various characteristics used for the identification process are presented in Appendix E.

Soft Clays

For these soils the parameters that were found relevant for their identification and used for the construction of the knowledge base are:

a) grain size distribution < 0.002mm
b) clay content $>50\%$
c) Atterberg limits (w_L, w_P, SL, I_P)
d) undrained strength (S_u) <25kN/m^2
e) unconfined compression strength (q_u) <50kN/m^2
f) SPT *N*-value <10
g) moisture content (w_n); varied but generally high
h) sensitivity (S_t) >1
i) compressibility >0.3

Expansive Clays

The characteristics of expansive clays that are important for their identification and hence stored in the soil characterization knowledge base are:

a) clay content
b) clay mineralogy : montmorillonite, illite, kaolinite
c) Atterberg limits (w_L, w_P, SL, I_P)
d) activity >1.25
e) expansion index
f) Unified Expansion Soil Index (ESI)

Soils classified as expansive clays generally have clay contents of 35% and above. The clay content is an important parameter in determining the activity of a soil as shown in Section 5.6. Soils with activity above 1.25 are classified as active clays. Active clays are generally expansive.

The presence of clay minerals susceptible to expansion is however the most important characteristic of these soils as the expansive behaviour solely depends on such minerals. Three main groups of clay minerals are distinguished namely kaolinite, smectite and illite. The most common clay minerals that cause expansion fall into the smectite group of clay minerals particularly the montmorillonites (Nelson & Miller, 1992). These clays are made up of layers of sheet structures. The layers, which are held together by weak van der Waals forces, are easily separated by cleavage or adsorption of water or other polar liquids. Imbibitions of water results in considerable volume change, which consequently, cause expansion of the soil mass. During dry periods, the loss of imbibed water due to evapo-transpiration processes may result in shrinkage, thereby posing problems to the structures founded on such soils. The presence of small proportions of these minerals in a soil could therefore cause considerable expansion or shrinkage depending on the availability of water. Illite with a similar structure to the montmorillonites expands slightly when wetted due to much stronger bonds between the layers of sheet structures. The kaolinites do not show any appreciable expansion when wetted. This results from much stronger hydrogen bonding and van der Waals forces between alternating silica and alumina sheets, which they are composed of (Mitchell, 1993). For a clay or soil to be expansive therefore, it must have some montmorillonite or illite clay minerals.

The Atterberg limits are a set of index tests performed on fine grained soils to determine the relative activity of the soils and their relationship to moisture content in order to distinguish between clays and silt. It is the primary form of classification for cohesive soils as shown earlier (see Figure 6.2). The details of the tests are found in widely used geotechnical engineering manuals (BS 1377: 1975; Head, 1982, ASTM D2487) and many soil mechanics textbooks. The soil properties sought from these tests are the liquid limit (w_L) and the plastic limit (w_p) from which the plasticity index (I_p) is obtained. Assessment of soil plasticity is by the plasticity index (I_p). Soils with large clay content remain plastic over a wide range of moisture contents and hence posses large plasticity index. Silts have low plasticity index. Clean sand and gravels have been considered as nonplastic. Nonplastic soils have I_p below 3.

Several classification schemes have been used in the literature to identify expansive soils based on these parameters as noted in Section 5.6. Obviously not all these parameters may be applicable or obtainable under any one situation. As a result the knowledge-based system was constructed with the view to making it useful to geotechnical engineers by using some of the most commonly used indices system. Two examples of such classification systems are the prediction of swell potential by means of activity of clays and the expansion index (ICBO, 1997). Where local practices vary considerably from the general practice, then the relevant local standards could easily be included in the system for it to meet local demands.

Collapsible Soils

The parameters stored in the knowledge base for the identification of collapsible soils are the grain size (silts and fine sand range i.e. 0.002 – 0.2mm), their open structure, low dry density (about 1.01 - 1.65gm^{-3}), high void ratio typically 0.8 and above and collapse potential above 1. The liquid limit of <45%, plasticity index of <25% and porosity of >40% were also included.

Liquefiable Soils

In the case of liquefiable soils the most important characteristics for liquefaction to be initiated are that the soil must be

a) cohesionless ($c = 0$ kN/m^2)
b) loose (low relative density of less than 35%)
c) saturated
d) grain size range should fall within the fine (0.06 – 0.2mm) and medium (0.2 – 0.6mm) sand fractions.

Therefore these characteristics were stored in the soil characterization and ground evaluation knowledge base.

Corrosive Soils

For corrosion to take place the soil must contain chemical components that may cause corrosive effects on construction materials such as concrete, steel and iron. Data stored for corrosive soils are the sulphate content, fluctuating groundwater table, and site location such as tidal zones, shorelines and soil type such as sanitary landfill.

Frost Susceptible Soils

Data stored in the soil characterization and ground evaluation knowledge base for the identification of frost susceptible soils are degree of saturation, soil type (generally intermediate soils such as silts and fine sands and to a lesser degree clay), hydraulic conductivity, frost susceptibility, shallow groundwater table and plasticity index. In addition to these is the climatic zone. Frost susceptibility is only possible in climates where ground freezing is possible and therefore unthinkable in tropical weather conditions.

Organic Soils

The characteristics that were found to be relevant for the identification of organic soils and therefore stored in the knowledge base are the fibre content, ash content, organic matter content and moisture content. For the identification of highly organic soils, field data such as colour, odour, spongy feel and fibrous texture have been included in the knowledge base.

6.3.2 The Rules

The system uses production rules to identify the type of problem soil. In general, production rules comprise an ***if*** portion and a ***then*** section. The following example illustrates how the rules predict the type of problem soil.

Example 1: Identification of loose sands.

Loose sands are granular soils with more than 50% of the coarse fraction in the sand size (0.075- 4.75mm) range. Some of the properties of these soils that are important in their identification alongside those of very loose sand, medium dense sand and dense sand are shown in Table 6.4. From the table it is noted that the most useful characteristics that could be employed in distinguishing the four types of sand are the relative density and the SPT *N*-value and these form the basis of distinguishing these types of soils.

Characteristic	Soil type			
	Very Loose sand	Loose sand	Medium dense sand	Dense sand
Granularity	Coarse	Coarse	Coarse	Coarse
Sand fraction	>50%	>50%	>50%	<50%
SPT *N*-value	<4	4 – 10	10 – 30	30 – 50
Relative density (D_r) %	<15	15 – 35	35- 65	65 – 85
Collapse potential	>1	>1	<1	< 1

Table 6.4: Some Characteristics of Poor Sandy Soils.

In the identification of loose sand, the most important properties found relevant for the purpose of this research work however are the granular nature, proportion of sand faction and most importantly the consistency in terms of SPT N-value and relative density. Properties such as the sand fraction and granularity are not too significant in distinguishing loose sand from very loose, medium and dense sand. They could however be useful in the identification of the sands from other major soil types say clay, silt or gravel

To illustrate how the rules were derived a decision tree is shown in Figure 6.3.

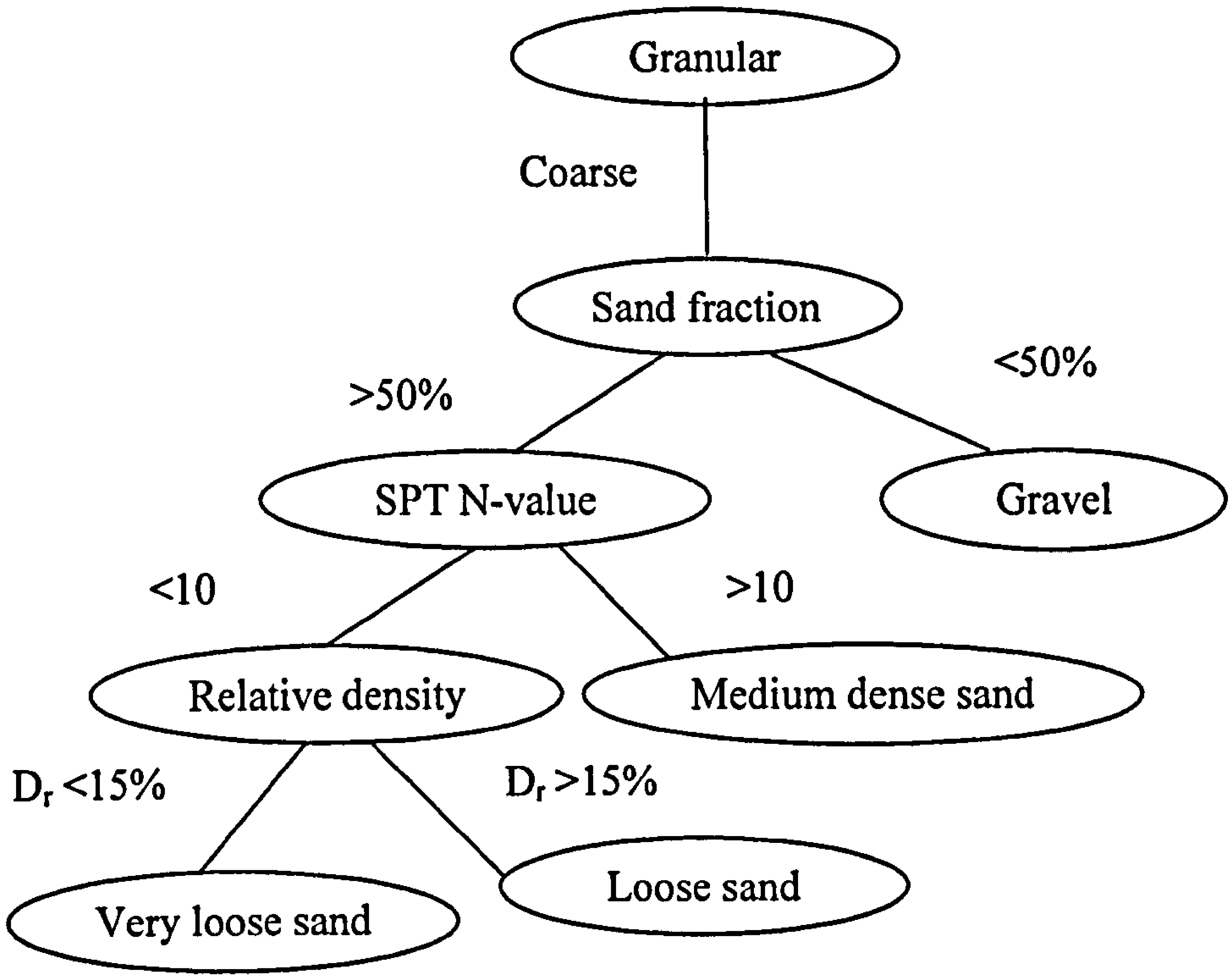

Figure 6.3: Decision Tree for the Identification of Some Coarse Soils

From the decision tree, Figure 6.3, the following rule set was generated for the identification of loose sand.

IF

Soil is granular

And sand fraction exceeds 50%

And SPT N-value is less than 10

And relative density is greater than 15%

THEN

Soil is loose sand.

Similarly, very loose sand could be identified by the following rule set using the same decision tree.

IF

Soil is granular

And sand fraction exceeds 50%

And SPT N-value is less than 10

And relative density is less than 15%

THEN

Soil is very loose sand.

In the case of medium dense sand the rule set that could be used for its identification may be as follows.

IF

Soil is granular

And sand fraction exceeds 50%

And SPT N-value is greater than 10

THEN

Soil is medium dense sand.

The above data is a record of initial facts about very loose sand, loose sand, medium dense sand and dense sand. To represent this in wxCLIPS, these facts about the soils are stored in the ***deffacts*** construct (to be discussed in Section 6.5) identified as the **deffacts** knowledge base. The ***deffacts*** construct allows the specification of initial knowledge as a collection of facts. wxCLIPS then uses backward chaining rules to suggest the type of soil, which in this case is loose, very loose, medium dense or dense sand when the user provides the relevant answers to the query rules.

For the identification of weak compressible soils the most important factors are descriptions in terms of consistency, the undrained shear strength, the SPT N-value, unconfined compression strength and to some extent the moisture content. The properties that are used for the identification of the other problematic soils are shown in Appendix E. Depending on the extent of site investigation and laboratory testing not all these parameters may be available to the geotechnical engineer for the conclusive identification of the soil. However, the use of a significant majority of the data available would assist in a better identification process. The structure of the soil characterization knowledge-based system is shown in Figure 6.4.

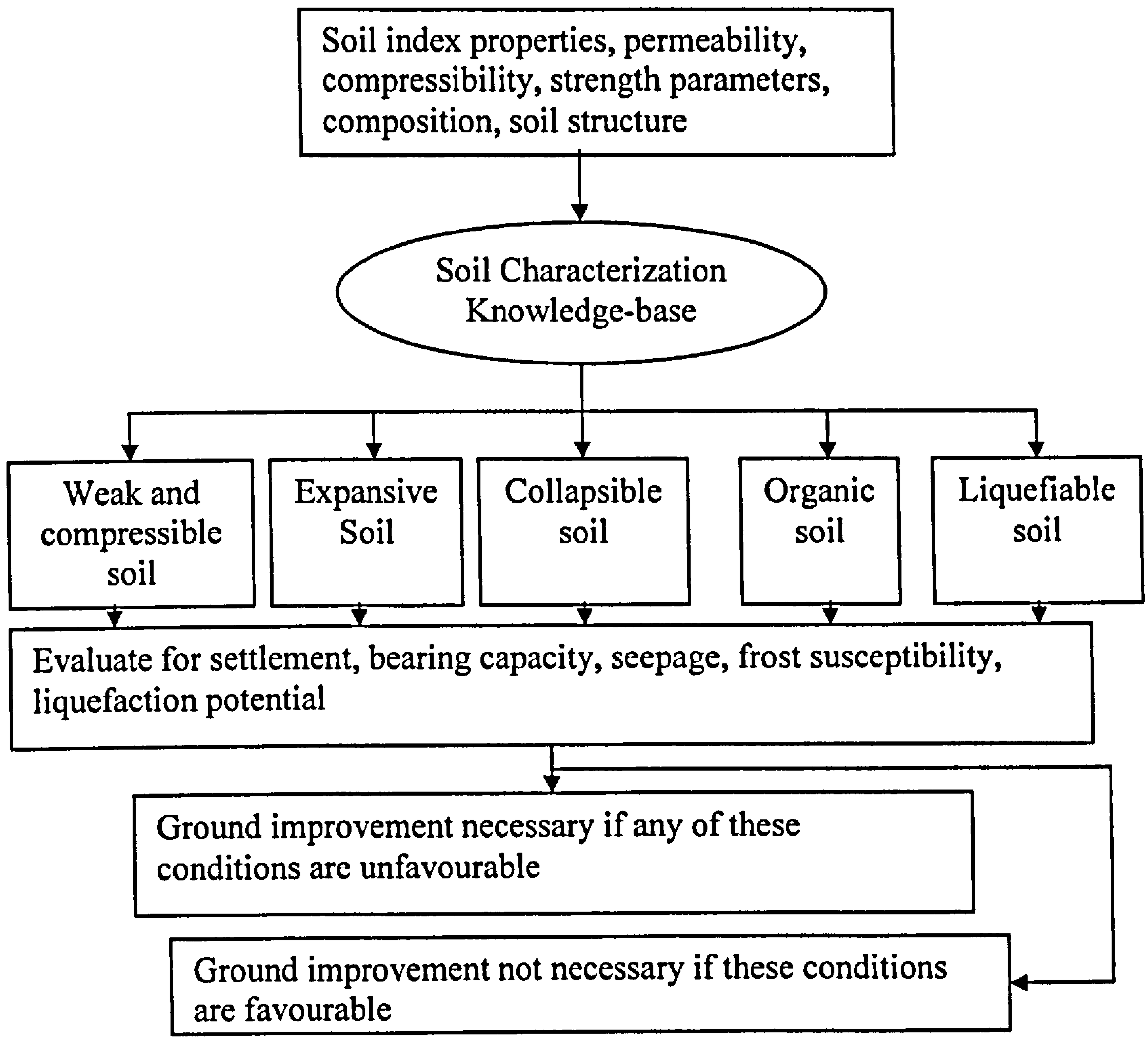

Figure 6.4: The Soil Characterization and Ground Evaluation Knowledge-based System.

6.3.3 The Evaluation for the Need for Ground Improvement

Having identified the type of problem soil underlying the site, the next essential step in the ground improvement method selection process is to conduct an evaluation process to ascertain that ground improvement is necessary since the presence of an underlying problem soil alone is not enough to warrant the use of a ground improvement methodology. The evaluation process can be carried out for both existing and proposed structures. In the evaluation process the various scenarios considered are in relation to the potential problems that may be posed to an existing structure or a proposed development when located on the site underlain by the identified problem soil(s). Based on the subsurface conditions together with the project performance requirements, a series of decisions need to be made in order to conclusively state whether ground improvement is necessary at the site for the facility. The rules for this process are designed to determine the need for a ground improvement technology when considering the establishment of a new facility or remedial works on an existing one.

Depending on the type of problem soil and the proposed facility, the various problems that may be encountered on problematic soils as discussed in Section 3.2 and for which an evaluation process is necessary are related to:

a) Settlement (differential and uniform) due to volume change following expansion, collapse or compression.
b) Stability.
c) Liquefaction.
d) Seepage.

The rules in this knowledge base evaluate the potential need for ground improvement by considering the effects due to the various forms of volume changes in soil such as expansion, collapse and densification, the effects of natural hazards such as earthquake, floods and landslides. Following a thorough assessment, advice is output on the need for ground improvement, where necessary.

Settlement and bearing capacity evaluations are invaluable for the establishment of new structures. The evaluation process determines the adequacy of the bearing capacity of the soil and the estimated settlement that the structure will undergo and if the values determined are within the permissible ranges. Allowable settlements for various structures have been given and discussed in Section 3.2. The bearing capacity is generally estimated by determining the factor of safety against bearing failure. If the factor of safety against bearing failure is adequate and the anticipated settlements are within the tolerable values, ground improvement may not be necessary otherwise there will be the need to improve the soil conditions.

Evaluation for settlement and bearing capacity are estimated by the static and dynamic loading conditions, the soil characteristics and the groundwater and seepage conditions.

Stability evaluation is determined by evaluating the soil state parameters such as unit weight/density, void ratio and relative density. The stress state is also determined by considering the vertical, horizontal/confining stress, shear stress and pore water pressure. In addition to these the effective friction angle and residual strength, shear modulus and volumetric strain are also determined. If the lateral deformation determined is greater than $0.67D_{ha}$ or if the settlement exceeds $0.67D_{va}$ (where D_{ha} and D_{va} are the allowable horizontal and vertical movements respectively of the foundation) then ground improvement is recommended.

The important parameter for consideration when determining for seepage is the coefficient of permeability (k) of the layer and any boundaries that may interrupt seepage. The permeability ranges of soils (to be dealt with in more detail later in this section) are shown in Table 6.5. The user selects from a list the degree of permeability of the soil.

k (m/s x 10^{-6})	Degree of permeability	Approximate soil type
>1000	High	Clean gravels
10-1000	Medium	Clean sand and gravels mixture
0.1-10	Low	Very fine sands
0.001-0.1	Very low	Silt, and mixtures of sand and clay
<0.001	Practically impervious	clays

Table 6.5: Permeability Ranges of Soils (after Somerville, 1986).

Ground improvement is recommended when the evaluation indicates;

a) Seepage quantity is less than allowable
b) Uplift pressure > allowable
c) FS < required.

6.3.4 The Method Selection Knowledge-Based System

Having identified the need for the use of ground improvement methodology for a project, the next step in the decision making process is to identify a suitable method to achieve the level of improvement that will be required to meet design specifications.

Thirty-two possible methods that have been classified into 8 groups on the basis of performance, mode of application and or objective have been included in the knowledge base. The methods are shown in Table 6. 6 in the form in which, they are represented in wxCLIPS.

Densification Techniques	**Consolidation Techniques**
Vibrocompaction	Preloading
Dynamic-Compaction	Preloading-with-Vertical-Drains
Blast-Densification	Vertical-Drains
Compaction-Grouting	Electro-osmosis
Roller-Compacted-Method	Vacuum-Consolidation
Reinforcement Techniques	**Electrotreatment**
Mechanical-Stabilization	Electrokinetic-Remediation
Soil-Nailing	Electroheating
Soil-Anchoring	Electrokineting-fencing
Micro-Piles	Bioelectrokinetic-Injection
Stone-Columns	
Fibre-Reinforcement	**Thermal stabilization**
Geosynthetics	Ground-Freezing
	Vitrification
Weight Reduction Techniques	
Light-Weight-Fill	**Chemical Treatment**
	Permeation-Grouting
Biotechnical Stabilization	Jet-Grouting
Brush-Layering	Deep-Soil-Mixing
Contour-Wattling	Fracture-Grouting
Reed-Trench-layering	Lime-Columns
Brush-matting	Cement Stabilization
Live-Staking	Lime Stabilization

Table 6.6: Ground Improvement Methods.

Most of the methods commonly used by the ground improvement specialists are included. Some of the innovative methods such as rapid impact compaction and calcite in-situ precipitation system (CIPS) and the newly developed ones have been excluded from the list due to lack of sufficient data and also because these methods are not widely known or used by many experts. Exclusion of these methods, however, does not undermine their significance in the improvement of problematic soil masses.

The selection of a method or combination of methods for a particular project is governed by several factors, which need to be thoroughly addressed before implementation of the project. The major factor controlling the use of an improvement method is the type of soil(s) underlying the site. The soil characteristics therefore play a significant role in the decision making process.

Results from the soil characterization and ground evaluation knowledge-base are used by the rules in this knowledge-based system to suggest ground improvement methods that would be suitable for the project under consideration. The method selection knowledge-based system uses facts centred on the detailed soil characteristics, other ground conditions such as groundwater levels and geological relations, the type of structure, economic considerations, construction constraints and numerous other factors, including regional practices, as discussed in Chapter 5, which contribute immensely towards the successful implementation of the method. The user is presented with a list of selected methods or a method that could be applied to improve the soil properties with the objective of confirming if it is suitable for the location of the proposed facility. For each method output, a degree of certainty is attached to demonstrate a measure of the reliability of the conclusion. In cases in which more than one method is selected, the system identifies them all by arranging them in order of preference with the most appropriate method having the highest certainty factor at the top.

Method Selection Criteria

On the basis of the interviews conducted and data gathered from the literature, the numerous factors identified and which play a crucial role in determining the suitability of a ground improvement method for a project are as follows:

a) Type of facility and loading condition.
b) Ground conditions.
c) Site conditions.

d) Construction related issues.
e) Environmental considerations.
f) Regional practices.
g) Availability of expertise or skilled labour.
h) Availability of construction materials.
i) Budget and availability of contractors.
j) Successful performance on similar sites in vicinity of plant.

Each of these factors is specified through a system of sub conditions. The selection of a suitable method or methods can be fulfilled in many ways based on a complex integration of the above listed factors. It is therefore difficult to index them to make a choice of a method. Data related to these conditions were stored in the method selection knowledge base for the decision making process.

Type of Facility

Ground improvement projects are usually resorted to when a type of structure is to be established at a site with inadequate soil properties or to existing structures on such soils. The complex nature of current day facilities may be one of the contributing factors to the use of ground improvement technology as an apparent common construction practice. A diversity of structures such as quays, wharfs, tank farms, multi-storey and single-storey buildings, tunnels, bridges, slopes and general excavations have been developed on poor soil formations. The nature of the structure is an important factor in the ground improvement method selection decision process.

However, structures impose varying load intensities on the subsoil, depending on the facility type and utilization. Loads from the various parts of the structure may differ when considered as individual units for instance floors and foundations. In order to avoid complexity in the load representation, it was thought that the overall load from the structure should be used. The load imposed on the subsurface soil is therefore assessed using three categories namely heavy, moderate and light (Table 6.7). If the overall structural load does not exceed $50kN/m^2$ the loading is described as light. Loads exceeding $200kN/m^2$ are classified as heavy. Loads in the range of $50 - 200kN/m^2$ are considered to be moderate.

Load classification	Structural unit		
	Floor kN/m^2	Foundation kN/m^2	Overall structure kN/m^2
Light	< 20	<50	< 50
Moderate	20 – 50	50 – 100	50 – 200
Heavy	> 50	> 100	> 200

Table 6.7: Load Classification.

Comparing a multi-storey domestic facility with a medium high-rise structure of say 3 storeys, and a single-storey domestic building, the loads imposed by these structures on the foundation soil varies from heavy through moderate to light respectively. If the type of structure is known therefore, then the loading condition can be predicted. Data on the type of facility could therefore be presented as user supplied information while the loading condition is stored as a fact in the knowledge base of wxCLIPS.

To represent this record of load and type of facility in wxCLIPS, the values about the load (heavy, moderate and light) are stored as facts in the ***deffacts construct*** (see section 6.5) with the facility type data stored in the ***defrule construct*** (see section 6.5). wxCLIPS therefore recognizes loads imposed by all single-storey domestic structures, for instance, to be light when the user selects this option as the type of facility.

The Ground Conditions

One of the most important and foremost considerations in the selection of a ground improvement technique is the subsurface condition. The ground condition involves an evaluation of a number of important factors that relate to the ground. The data stored under the ground conditions relate to the following factors:

a) Type of soil that needs to be improved.
b) Depth and thickness of the soil stratum that needs to be treated.
c) Extent of the layer under consideration that needs to be treated outside the footprint of the facility.
d) Number of layers to be treated if different strata underlie the area (soil stratigraphy).

e) Saturation level of the soil.
f) Level of groundwater table.
g) Permeability of the layer or individual layers under consideration.

The rules in this section are therefore based on these factors so that the user selects an appropriate answer from a number of options provided in order that reasonable conclusions can be drawn in the method selection procedure.

The significance of the soil characteristics has already been discussed in the earlier sections. Based on these characteristics namely; strength, bearing capacity, compressibility, expansion properties, collapse potential, liquefaction potential, organic matter content and frost susceptibility, the various problem soils have been defined. The characteristics of the soils dictate the purpose for which an improvement should be conducted. Ground improvement techniques are normally carried out with the following broad objectives, which are stored as facts in respect of the objectives of improvement and shown in the manner in which they are represented in wxCLIPS:

a) bearing-capacity-increase
b) settlement-control
c) lateral-stability
d) environmental-control
e) seepage-control and
f) increase-liquefaction-resistance

These facts are however soil type dependent. For instance weak granular soils are characterized by having low strength values and consequently low bearing capacities. The major objective of improving the properties of such a soil will be to increase the bearing capacity when loaded by a load imposing structure or increase lateral stability when slopes or excavations are involved, rather than to control settlement. To achieve such objectives requires the use of techniques that would densify the soil. Similarly, soft cohesive materials apart from possessing low strength values are also compressible. When subjected to loads, these soils consolidate thus resulting in settlement. The presence of such soil in a site under consideration will require improvement methodology that will address settlement problems, bearing capacity and lateral stability. Each problem soil type is linked to an objective or objectives of improvement so that as the user selects a soil type wxCLIPS identifies the objective of improvement.

As indicated earlier in Section 6.3 the depth and thickness of the problematic soil stratum also play an important role. The improvement of soil properties by the application of the common ground improvement techniques can be carried out by the use of shallow or deep ground improvement techniques. Some examples of shallow ground improvement techniques as shown in Fig 6.1 include surface compaction, lightweight fill, geotextiles, cement and or lime stabilization and pre-mixed soil methods. The depth to which these methods can improve the soil is limited to 3m. Deep ground improvement methods include deep mixing methods, vibroflotation method, vertical drain technique and the preloading method to mention a few. These methods are applicable up to depths greater than 3m. Some of the deep ground improvement methods such as the blasting method have been used to improve soils to depths greater than 30m. Therefore, knowing the depth of occurrence of the problem soil narrows down the number of methods to consider in addition to, guiding the engineer to select the most appropriate method. At extreme depths, the feasibility of employing the use of certain methods, such as vertical drains, becomes difficult and may even be virtually impossible due to technical issues with regards to installation equipment, which may consequently increase the overall cost of the project.

On the basis of depth of problematic soil formation from the ground surface, two classes of depth were therefore established as follows:

a) shallow (<3m)
b) deep (>3m)

The selection of a depth value of 3m as the boundary between the two depth regimes is arbitrary. The two depth properties shallow and deep were therefore stored in the working memory of wxCLIPS such that depending on the input data provided by the user, the most applicable methods are considered. Clearly, therefore if the depth of problematic soil at a potential location site is considered to be shallow, it will be considered totally unsuitable to use a deep ground improvement method for the improvement of such a site.

The use of any method still depends on a number of further considerations. For instance, when relatively thick overburden cover is encountered the deep ground improvement method selected should be one that is capable of penetrating the type of overburden materials overlying the problematic soil at depth. On the contrary, when thin or no overburden material overlies a problematic soil such as soft clay or weak materials, the use of methods that are installed by means of heavy equipment may necessitate the introduction of more competent foreign coarse granular material to form a working platform for such equipment.

Similar to the depth of formation, the thickness of the problematic soil stratum also plays a significant role in the decision making process. Generally, it is recommended that for adequate results, the entire thickness of the poor soil stratum should be improved. This recommendation may however have some economic implications apart from technical issues that may be associated with each methodology in addition to the type of facility. The different methods have limitations on the depths to which they can effectively alter the poor soil properties so that the thickness of the stratum to be improved plays a key role in the method selection process. Depending on the loaded area, the common practice is to improve say the upper 5m of a thick stratum. Three categories of layer thickness that would be considered for improvement were then distinguished. These are

a) thin
b) average
c) thick

A thin stratum is considered to be 0.5m or less. If the layer thickness is between 0.5 and 2m it is considered as average thickness whiles a layer measuring over 2m will be classified as thick. Layer thickness is therefore assessed by thin, average-thickness and thick.

Soil stratigraphy is one of the many contributing factors to the selection of a ground improvement method. The facts about soil stratigraphy relate to layer uniformity, lateral and vertical variations, layer disposition and stratigraphic relations of the various layers. Where a uniform poor quality substratum underlies the site, a single method could be applied to improve the quality of the material. However in situations where the geology is complex, the different geological formations may present different poor conditions and hence influence the method(s) that can be used. The complexity could be lateral or vertical. If the geology suggests inter-layering of both competent and incompetent units the improvement program could be conducted by selectively treating the incompetent layers of soil using some of the methods that are applicable under such situations. To account for the stratigraphic relations at the site, assessment is done with reference to parameters such as layering, layer uniformity and disposition. The overall stratigraphy is assessed as either complex or simple (Table 6.8). A complex stratigraphy is one that is stratified, inhomogeneous and dipping. Simple stratigraphy refers to a uniform, non-dipping and homogeneous soil layer.

Stratigraphy	simple	complex
Layering	Non-stratified, uniform	Stratified (more than one layer)
Layer uniformity	Laterally-homogenous	Laterally-inhomogeneous
	Vertically-homogeneous	Vertically-inhomogeneous
Disposition	Horizontal	Dipping

Table 6.8: Assessment of Site Stratigraphy.

Another important subsurface condition factor for consideration in the method selection process is the degree of saturation of the problem soil. Three classes of soil saturation levels are defined namely fully saturated, partially saturated and absolutely dry. For a fully saturated soil, the degree of saturation is 1. An absolutely dry soil has zero degree of saturation, while partially saturated soils degree of saturation ranges between these two extremes. Some methods are suitable for saturated soil formations whiles others are good for unsaturated soils. If the soil is particularly dry, some methods such as chemical stabilization techniques that involve some chemical reactions between the soil and the stabilizers will be unsuitable. The groundwater level may influence the degree of saturation of the soil depending on its position in relation to the soil stratum under consideration. The parameters of the depth of groundwater table (WT) used in this system are:

a) WT- high (i.e. shallow)

b) WT-moderate (i.e. intermediate)

c) WT-low (i.e. deep)

The groundwater table could also be described as permanent or temporary. A temporary groundwater table may be oscillatory due to weather changes (dry and wet conditions), or even perched as a result of the presence of pockets or lenses of impermeable strata.

Soil permeability is described as that property of soil, which permits flow of water (or any other liquid) through its pores or interstices. Permeability is an important soil parameter for any project where flow of water through soil or rock is a matter of concern (for example, seepage through or under a dam). Highly pervious soil permits the free flow of water through it easily, whereas impervious soil possesses very low permeability and water cannot easily flow through it. Permeability controls the stability of soil masses. It is also an important factor in many soil engineering problems such as the settlement of buildings and liquefaction. In ground improvement methodology, the permeability of the soil becomes important when considering the use of drainage techniques for the improvement of the soil or in the assessment of liquefaction potential of the soil when using methods such as dynamic compaction.

Permeability is usually evaluated by the coefficient of permeability, *k*, which is defined as the velocity of flow, which would occur under unit hydraulic gradient. The various classes of soil permeability based on the coefficient of permeability *k*, which have been stored in the knowledge base are shown in Table 6.9 (see also Table 6.5) and depending on the range of values of *k* entered by the user, wxCLIPS identifies the permeability (drainage property) of the layer under consideration as pervious, semi-pervious or impervious.

Coefficient of permeability (k) m/s	Drainage property
10^{-3}	pervious
10^{-5}- 10^{-3}	semi-pervious
10^{-5}	impervious

Table 6.9: Coefficient of Permeability of Soils.

A summary of some of the facts relating to the subsurface conditions that are stored in the knowledge base are shown in Table 6. 10. The selection of a method will depend on how favourably these factors interact.

Factor					
drainage	depth	groundwater-condition	thickness	layer-extent	stratigraphy
Pervious Semi-pervious impervious	shallow deep	WT-high WT-moderate WT- low Permanent Temporary	thick average thin	Wide Non-extensive	simple complex

Table 6.10: Representation of Ground Conditions.

The overall evaluation of the ground condition is assessed by three terms poor, moderate and good. Good ground condition represents the situation where there is no evidence of the presence of problematic soil underlying the site and where there is no worst condition of each of the factors listed above. On the other hand if the assessment of the ground condition is poor, then all or most of the factors under consideration do not match standard requirements.

Site Conditions

The presence or absence of certain site conditions affects the feasibility or cost of the ground improvement project. In order to account for the influence of site conditions therefore, the following sub-conditions found to be the most influential in the decision process, were considered.

a) Size of area (large or small).
b) Confinement of site.
c) Interference due to buried or surface structures or utility lines.
d) Effect of method application on nearby sensitive buildings or facilities.
e) Accessibility (accessible, inaccessible).
f) Evenness of surface.
g) Stability of surface.

The size of the area to be improved plays an important part in the decision making process. Limitations in the size of a site for a project have many implications and could dictate the type of ground improvement method to use. Dynamic consolidation for instance, requires an area of 8,000 to 10,000m^2 to be economic (Bergado et al, 1996b) and hence will not be suitable for the improvement of an area less than this. A method such as the vertical drain technology has also been found to be more suitable for large areas. For very small sites, the use of methods that will involve high mobilization cost will be uneconomic. Methods that require the use of very heavy and/or bulky equipment may also not be suitable for such sites due to limitation on space to mount the installation equipment. For small-scale projects, the most suitable methods include ground freezing and permeation grouting methods. The use of such methods for large projects may not be particularly advantageous.

In order to account for the site area, the size can be described as either small or large so that facts regarding project site area are stored as.

project-site–area small

project-site-area large

No numeric values are used to describe the site area, but it is thought that the user will use relative terms based on his or her judgement.

Open areas may be the most favourable sites for the application of most (if not all) ground improvement methods and particularly those whose mode of application could cause considerable damage to existing infrastructure. Some methods such as dynamic compaction and the in-situ soil mixing technique involve the use of equipment that requires sufficient headroom. The use of such methods in areas with low headroom such as tunnels and other underground facilities may not be practicable. Areas with a network of installations such as overhead power cables, which constitute surface obstructions and buried utility lines that form subsurface constraints, may also not be ideal for the use of some techniques as these installations tend to hinder the smooth operation or installation of the method. These factors together are described as site restraint because of the hindrance to the smooth installation of some ground improvement methods. Site restraint is assessed by two conditions as either site-restraint high or site–restraint low. Low site-restraint refers to a condition where no obstructions or obstacles either in terms of size of area, confinement, surface or sub-surface structures inhibit the use of a method.

Site accessibility may also play a significant role in the method selection process in terms of supply of materials, transportation of construction equipment or the transfer of the work force to and from the site. Inaccessible sites hinder the ease of transporting equipment, workmen and materials particularly when heavy equipment is to be used. On the other hand if the site is accessible, then the means by which accessibility is accomplished will also play a significant role. Consequently, site accessibility may be described by type such as rail transport, road transport, water transport or other means of carting. Site accessibility is therefore represented by the following terms: accessible and inaccessible, depending on which one of these that is applicable.

It is also thought that the surface relief may play a crucial role when considering the use of some methods. In the installation of vertical drains for instance very even terrains have been found to be most suitable as compared to a rugged landscape. The movement of equipment is also much more enhanced on even surfaces than on very undulating ground surface. To account for surface topographic effects it was thought appropriate to represent this feature as follows,

site-topography even

site-topography uneven

The stability of the site may also need to be considered when the construction or installation of a method of improvement involves ground vibrations. Stability is assessed by two terms; high and low and represented by:

site-stability high.

site-stability low.

Instability could result from ground vibrations due to the method of application and particularly when slopes are involved. The question of stability arises when there are other structures in close proximity to the site.

Each of the aforementioned factors is important in the method selection process. There are significant differences, however, in the relative importance of each factor when considering the different methods. Several decision tables can be constructed by considering these sub conditions when deciding to use ground improvement. The overall site condition is assessed as either poor or good based on which of the afore-mentioned factors that dominate. A site with high sight restraint may be unsuitable for the application of certain types of ground improvement such as the dynamic compaction method and as such would result in the overall assessment of the site condition as poor. Table 6.11 gives a summary of the sub conditions under the condition state site-condition poor.

site-condition	poor	
site-restraint	high	low
site-stability	low	high
site-topography	uneven	even
site-accessibility	inaccessible	accessible

Table 6.11: The Sub Condition States under Site Conditions.

These sub conditions states can combine in various forms for the selection of an appropriate ground improvement method. For instance a combination of site-restraint low, site-stability high, site-topography even and site-accessibility inaccessible may result in the assessment of a site-condition as poor mainly due to the inaccessibility of the site. The use of some ground improvement techniques for example vibrocompaction, may be unacceptable or uneconomic because there is no easy access for the transportation of installation equipment even though other conditions such as the low site restraint, high site-stability and even topography may favour the use of this method.

Construction Related Issues

This is also specified by a number of sub conditions as listed below.

a) Time

An important factor considered is construction scheduling: that is the time when the improvement results would be felt. This could be classified into three time frames namely

a) immediate improvement
b) long-term improvement
c) initial improvement and then a continuing strength gain (e.g. explosive compaction method and methods involving cementation reaction).

If the time schedule is not too tight, some methods that by their mode of application can adequately improve the properties of the soil but over a long duration of time (e.g. preloading technique) may be more feasible and cost effective than others. On the other hand if the improvement is immediately required such methods will be inappropriate. Other methods such as some stabilization techniques yield immediate improvement results and continue to improve the properties of the soil over a period of time.

Similar to the above other factors construction-time-schedule is represented by

- time-requirement immediate
- time-requirement long
- time-requirement immediate-continuous

b) Maintenance-requirements

Maintenance-requirements are indicated as one of the construction considerations. Methods that require the use of equipment that may periodically break down and need to be put in service may contribute significantly to the decision making process. Maintenance-requirements is represented by yes or no to indicate if the requirement is necessary or not.

c) Material-durability

When foreign materials are to be introduced into the soil or ground, consideration must be given to the significance of durability of such materials. If the environment into which the materials are introduced is hostile, the likelihood is that these materials deteriorate at a fast rate thus rendering the improvement objective useless. Material-durability is represented in this system by high and low to indicate the expected durability of materials used.

d) Availability of Construction Materials

Some ground improvement methods are carried out by the introduction of foreign materials into the soil or placing the foreign material on the soil. The preloading technique and the light-weight-fill are examples of such methods that require the use of large volumes of borrow fill materials and water filled reservoirs. If the preloading method is to be used consideration must be given to the type of material to use, its availability or proximity and cost in terms of haulage where applicable. When borrow fill is to be used haulage distances must be within economic reach. The economic haulage distance is set at 15km from the site of loading. Material availability is thus further specified by haulage distance.

Other materials that have been used are rock or sand aggregates, colliery spoil etc. If consideration is given to the use of methods that rely on such materials, it is important to verify their availability before the method is considered. Material-availability is therefore represented by highly-required and not-required.

e) Availability of Expertise or Skilled Labour.

The ease of construction of any improvement method is influenced by the availability of expertise and or skilled labour. Expert advice is necessary for quality control and efficiency. For each of the methods the services of an expert may be required for it to be successfully applied. Apart from the expert, there may also be the requirement for experienced or skilled labour. The implementation of some methods of ground improvement may require the use of both highly skilled labour and experts for example the stone columns method whereas for other methods such as the preloading technique, the presence of an expert to direct and guide semi-skilled or unskilled labour may be sufficient to conduct the installation of the method. The requirement for expertise is simply represented by high or low while labour-requirement is assessed as skilled, semi-skilled or unskilled as shown below to represent facts about the requirement for expertise or skilled labour in the application of a particular method.

expertise-requirement high.

expertise-requirement low.

labour-requirement skilled

labour-requirement semi-skilled

labour-requirement unskilled

f) Equipment Availability

One of the construction related issues that need to be considered is the availability of equipment. The type of plant and equipment available to the contractor or within his reach also plays an important role in the method selection process. For example, dynamic compaction contract can be performed by using conventional cranes to drop 6 to 18 tonnes weight from heights of up to 20m to make the method cost-effective. Specifications of tampers heavier than 18 tonnes may require the use of non-conventional equipment such as the Lampson LCD-350 thumper (ASCE, 1997) and its availability must therefore be assessed. Since ground improvement methodology is a highly technical area, the use of inappropriate equipment for the construction of the method may result in sub standard or poor quality work that may have serious consequences should failure occur. As a result the engineer or consultant must ensure the availability of adequate construction equipment. The availability of equipment is assessed by yes or no.

The general assessment of construction-related-issues is by the terms important and unimportant. Where the assessment is indicated as important, then most or all of the conditions stated above are significant in estimating this condition. Table 6.12 gives a summary of the condition states necessary for the development of a decision table (Table 6.13) for construction related issues with the condition state important. It must be stated that the arrangement in Table 6.12 is arbitrary and does not follow any particular trend as various combinations can result. Similar tables can be constructed for the converse condition state.

From Table 6.12, the various ground improvement techniques that can be used for the immediate improvement, long-term improvement and initial improvement with continuous strength gain of a problematic soil when considering the maintenance-requirement and material durability factors are shown. The decision table suggests that the vacuum consolidation technique for instance, can appropriately be used where installation material durability is high, immediate improvement is required and where maintenance of installation equipment may or may not be necessary.

Construction-related-issues	important								
Time	Immediate improvement			Long-term improvement			Initial improvement and continuing strength gain		
Maintenance-requirement	yes	no		yes	no		yes	no	
Material-durability	high	low		high	low		high	low	
Equipment-availability	yes	no		yes	no		yes	no	
Expertise-requirement	high	low		high	low		high	low	
Labour-requirement	us	ss	s	us	ss	s	us	ss	s

Table 6.12: Construction-Related Issues Condition States.

Notes: us = unskilled; ss = semi-skilled; s = skilled

Time	Immediate improvement				Long-term improvement				Initial improvement & continuous strength gain			
Maintenance-requirement	yes		no		yes		no		yes		no	
Material-durability	H	L	H	L	H	L	H	L	H	L	H	L
Vacuum consolidation	+		+									
Preloading					+	+	+	+				
Vertical drains	+	+	+		+				+			
Blasting	+	+	+	+					+	+	+	+
Light-weight fill					+	+	+	+				

Table 6.13: Decision Table for Construction-Related Issues.

Notes: H = High; L = Low

Economic-considerations

a) Budget

Having considered all the possible factors that affect the suitability of a method one other most important factor is the cost of the project. The cost of the project is estimated by summing both direct and quadratic costs (Al Abo Omar & Mangin, 2003). Direct cost relates to materials, equipments and labour whiles the quadratic cost relates to waste cost, control cost, building site expenses and risk costs. Material cost encompasses the cost of input materials itself, packaging, transport, unloading, storage and placing. Equipment cost relates to rent, installation, maintenance, dismantling, transport, unloading storage and placing of the requisite equipment for the implementation of the method. Table 6.14 shows estimates of some of the costs components for some ground improvement techniques. The high mobilization or demobilization costs of the methods as displayed in Table 6.14 may render the use of such methods as expensive (e.g. in situ soil mixing).

Method	Mobilization/ Demobilization ($per drill rig)	Group pipe installation ($/m of pipe)	Injection labour and materials ($/m^3 of improved soil)
Compaction grouting	8,000 – 15,000	>50^A	>20^B
Permeation grouting			
• micro-fine cement	15,000 – 25,000	>50^C	>130^D
• silicates	>25,000	>50^C	>200^E
Jet grouting	>35,000	-	>320^F
In situ soil mixing	100,000^G	-	>100^H, >200^I
Drain pile	Not available	-	Not available

Table 6.14: Cost Estimates for Low Vibration Ground Improvement Techniques in the United States (adopted from Andrus and Chung, 1995).

Notes: A – group pipe 76mm in diameter; cost would double for low headroom work.

B – assuming volume of grout injected is 10percent of the total volume treated.

C – sleeve port pipes.; cost would double for low headroom work.

D – assuming clean gravel with sand, 20% grout take, and more than 200,000 litres grout.

E – assuming clean sand, 30% grout take and more than 200,000 litres of grout.

F – does not include handling and removal of the waste slurry.

G – approximate cost for large multi-auger rig and grout plant.

H – shallow mixing (say depths less than about 8m).

I – deep mixing (say depths between 8m and 30m).

These cost components constitute the construction budget, which must be matched against the available funds for the project. Should construction budget exceed available funds then the method under consideration may not be feasible due to lack of funds even though the method may prove to be the most appropriate and other alternative methods need to be considered.

The relative cost of site treatment using various improvement methods are shown in Table 6.15. For the same volume of soil, it is observed that the grouting methods are relatively more expensive than methods such as dynamic compaction and the vibro-compaction methods.

Method	Cost Description		
	Volume of treated soil ($/m^3$)	Area of treated ground ($/m^2$)	Relative costs
Dynamic compaction	0.7-3	~ 5	Low
Vibro-replacement	4-12	-	Moderate to high
Vibro-compaction	1-7	1 – 4	Moderate
Excavate-replace	10-20		Moderate
Surcharge/ buttress fill	-		Low
Mix-in-place walls and columns	40-80		High
Slurry grouting	160-525		Moderate
Chemical grouting	30-200	5 – 50	High
Compaction grouting	100 – 400		Low to high
Jet grouting	275 – 650		High
Freezing	-		High
Drains: gravel, sand, wick	100 - 150		Low to moderate
Deep soil mixing			High to very high

Table 6.15: Comparative Costs of Ground Improvement Methods.

Three classes of cost, low, moderate and high were defined to account for construction cost. Low construction cost refers to the situation where the construction budget estimates is below available funds. Average cost is a balance between construction budget and available funds. If the estimated construction budget exceeds the available funds, the cost of project is referred to as high.

b) Availability of Contractor

In addition to construction budget, the use of a method to improve the site conditions also depends on the availability of a contractor to carry out the work. If there are locally based contractors, the use of their expertise would considerably reduce the overall project cost than hiring the services of a distant contractor. In the latter case there may be considerable increase in indirect costs associated with transport and storage. For example, there are only about 5 to 8 specialist contractors in the U.S that routinely perform dynamic compaction (ASCE, 1997). Therefore, recommending the use of this method for the improvement of a site that is remote from the locations of any of these contractors maybe inappropriate as the overall cost of the project could escalate mainly due to mobilization. The local contractor may also have a better understanding of the ground condition based on the knowledge gained from previous projects within the locality and this may lead to reduction in construction time as solutions to problems encountered due to unpredicted changes in ground conditions may easily be found.

To account for cost therefore, the user is expected to input which category of cost components best describes the situation under consideration. Three condition states of relative cost namely low, moderate and high were established. The overall cost is then matched with the available funds.

Environmental Considerations

Many of the conventional methods of granular soil improvement techniques, such as stone columns, dynamic compaction, and vertical drain installation create considerable noise and vibration during construction. The recommendation of such methods will be dependent on the effects these will have on the environment particularly in built up environments. If vibration levels are high, this could trigger off stability problems in unstable ground and also cause damage to sensitive facilities. The relationship between noise level and the distance from the source of noise for several ground improvement techniques is illustrated in Figure 6.5 (Ando et al., 1995). From the figure, the installation of sand compaction piles produces the most undesirable noise above average at a distance of 25m from source. The deep mixing method can be carried out at distances as close as 5m. This value may be much higher for other methods.

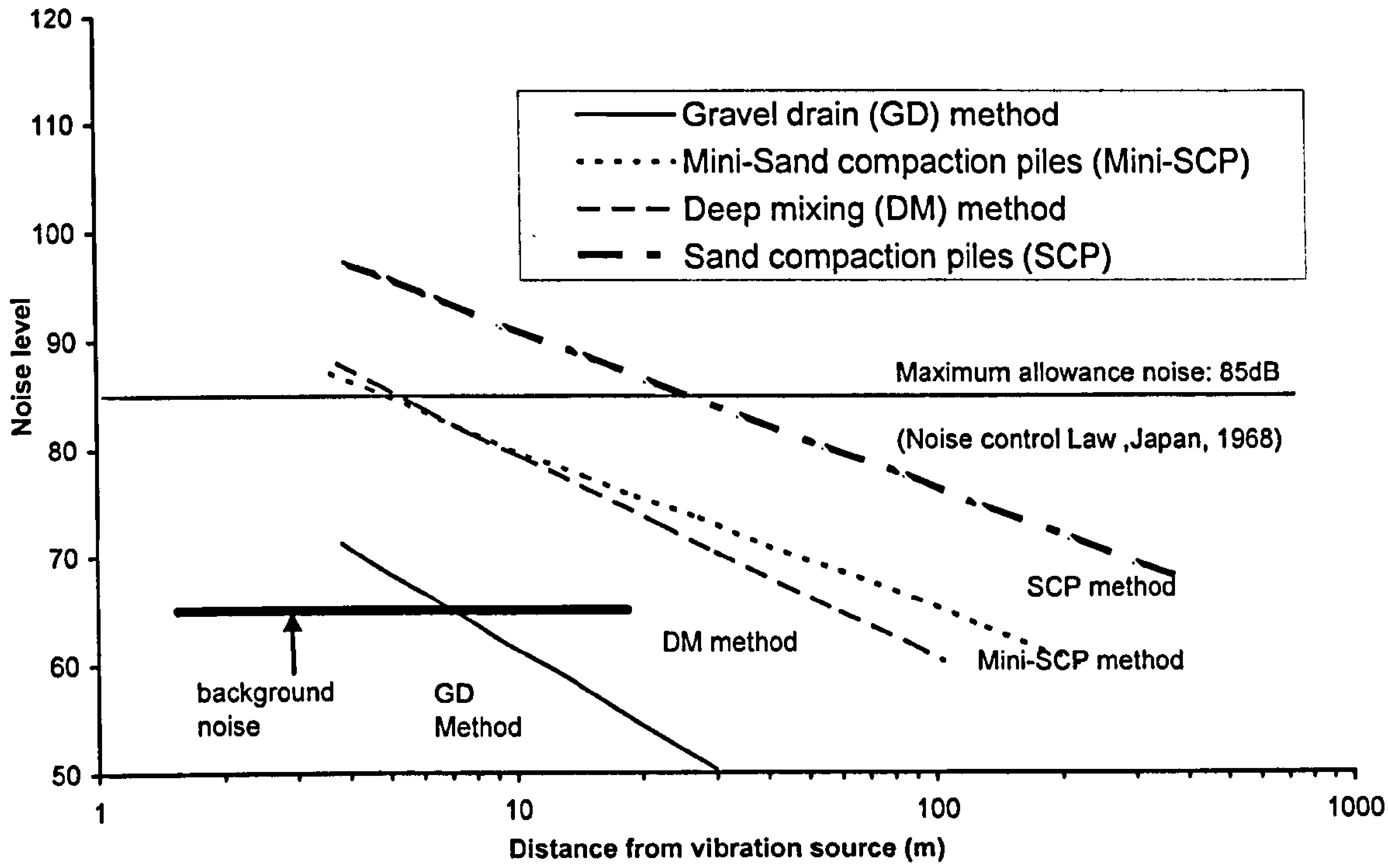

Figure 6. 5: Environmental Impact of Noise due to Various Ground Improvement Techniques (after Ando et al, 1995)

Other environmental issues may arise from pollution of both surface waters and groundwater particularly in areas underlain by pervious strata as some of the methods result in discharge of large volumes of fluids during the construction period. The discharged fluids may enter the surface streams or even infiltrate into the groundwater regime resulting in contamination of these water bodies.

The impact of factors such as pollution, noise or vibrations on the environment can be described in terms of low, moderate and high effects. These therefore become the facts for environmental impact and are represented as:

environmental-impact low.

environmental-impact moderate.

environmental-impact high.

Thus in the case of noise, *environmental-impact low* stands for low noise levels if the installation of the method results in low levels of noise. The other two represent moderate noise and high noise levels. Similarly, if the installation of a method results in ground vibrations or pollution, the impact on the environment is equally represented as above.

Regional Practices and Tradition

The theoretical bases on which many of the common ground improvement methods operate may appear uniformly accepted in most of the regions where ground improvement technology is frequently used however, there are remarkable differences in the state-of-the-art of ground improvement methodology worldwide. In the first instance regional classifications of the methods commonly employed differ on the bases of methods regarded as ground improvement methods, reinforcement methods and treatment methods. It could be stated that some of these classification schemes are based purely on the mode of application of the method(s) such as inclusion methods as with the ISSFE classification scheme the SIG classification system in addition to traditional or historical associations. Differences in the classification schemes may bear some amount of influence on the method selection process.

Where tradition is the most influential factor, a method with historical associations to a region would be almost certainly preferred to other methods alien to such an environment counting on several other factors such as availability of expertise, equipment and or skilled labour considerations and firmly established theoretical bases. The drainage method for example, has been used for a number of liquefaction remediation projects in Japan, yet it has found limited use in the United Sates (Andrus and Chung, 1995). In Belgium, it is observed that the most popular and commonly used methods are the stabilization methods such as lime and cement stabilization. The majority of these methods are used to control settlement and bearing capacity. Methods such as dynamic compaction, vacuum consolidation, blasting, compaction grouting and deep soil mixing are seldom used, whereas methods such as hydrofracture grouting, fibre reinforcement and electro-heating had never been used as at 1997 (see Van Impe et al, 1997a). In the US, the most commonly used methods include stone columns and compaction methods. Results from the questionnaire indicate that the electro-heating method is not particularly used in the UK as none of the interviewed experts has used or intend to use this method. The deep soil mixing technique is common in Japan. In general, the most frequently used techniques globally are the vibro techniques such as vibro compaction and vibro replacement including dynamic compaction and the grouting techniques.

Due to a polarization of the usage of methods, it was thought to classify the methods into regional usage and global usage. It is however thought that the use of the methods in a particular region or country may also be controlled by factors such as the common soil formation. For instance in the Scandinavia the soils are generally soft and compressible and methods that would be suitable for the improvement of such soils would not include such methods as the dynamic compaction method, which apart from being used for densification purposes will require the use of heavy equipment and consequently a working platform to mount such equipment.

It may be observed from the foregoing that for the selection of any particular method not all these factors may be applicable. Whereas the presence of some of these conditions will favour the use of one particular method of ground improvement, the absence of the same conditions or a set of conditions may favour the use of another. When considering the use of the dynamic compaction for example, the conditions that have been considered to be the most important are shown in Table 6.16.

Condition	Specific Requirements	Remarks
Soil characterization	loose granular soil	
Degree of saturation	partially saturated	above water table
	saturated	below water table
Permeability	pervious soil	clay content <25%
	semi pervious soil	PI<8
Headroom	high enough	0<PI<8
Maximum depth of treatment	10m –12m	

Table 6.16: Important Conditions to Consider for the Selection of Dynamic Compaction

Other factors that may be considered include the following:

a) Availability of construction equipment
b) Site location
c) Extent of site
d) Time constraints
e) Compaction procedure
f) Requirements for foundation design
g) Type and availability of backfill material

Some of the factors dictate or control others. For instance the type of facility dictates the loading condition, whereas the type of soil suggests the purpose for which the improvement is undertaken. For any type of facility on soft cohesive soil, the main objective of the improvement will be, in the first instance, to reduce settlement. Other objectives may be to increase bearing capacity or to increase stability. For a specified structure such as a tower block the load imposed on the substratum material will be interpreted as heavy whereas for a single storey building the load imposed on the subsurface material is considered to be low. The conditions under which the other methods of ground improvement are selected are presented in Appendix F

6.4 The Certainty Factor Model

The issue of reasoning with limited knowledge and incomplete information that may be associated with the method(s) selected, necessitated the application of certainty factors (CF) to the selected methods so as to account for these uncertainties and modelling some aspects of the reasoning process of the ground improvement domain experts. The introduction of certainty factors was found necessary because ground improvement is fraught with a number of uncertainties and as such it was necessary to assign a certainty factor to each piece of information in the system. The certainty factor, CF, shows the net belief in a hypothesis based on some evidence. Certainty factors quantify the confidence that an expert might have in a conclusion that s/he has arrived at. In general, therefore, the certainty factor is used to express how accurate or reliable one judges a predicate to be. It is a judgment of how good ones evidence is and then how to combine various judgments.

Expert systems certainty is usually determined based on the following rules.

- The facts and relationships of the rules may contain uncertainty. The following statement could be used to explain this factor. If **these** conditions are met, **this** outcome almost always results. Once a while however different outcome results. For instance if the soil is loose granular and has fines not exceeding 15%, then certainly use the vibrocompaction method. It is also possible however that with these set of conditions the blasting method could be used to improve the soil conditions.
- The user may express doubt in an answer.

Numerical expressions ranging from 0.0 to 1.0 or 0 to 100 are often used to quantify uncertainty. A phrase such as 'suggestive evidence' is given a number such as 0.6 (or 60); 'strongly suggestive evidence' is given a number such as 0.8 (or 80). Table 6.17 illustrates a more elaborate expression of the certainty factors. The person making the judgment uses the scale more or less as an ordinal scale. The numbers are used in a metric to permit a computer to make calculations.

Certainty factor	Key word	Certainty factor	Key word
0	Never	0.6	Quite common
0.1	Very uncommon	0.7	Common
0.2	Uncommon	0.8	Very common
0.3	Not usual	0.9	Principally
0.4	Sometimes	1	Always
0.5	Neutral		

Table 6.17: Expression of Certainty Factors.

To account for a measure of disbelief, the certainty factors may be extended to range from some negative value to some positive value, say –100 to 100, defined in terms of measures of belief and disbelief, which is associated with a condition or an action of a rule. Where a certainty factor is –100, this would represent a complete lack of belief in the issue under consideration while a factor of 100 would represent an absolute belief in a rule or value. A certainty factor equal to zero indicates that the evidence does no influence the belief in the hypothesis. In more detail, each component of a condition may have a certainty factor associated with it. For example, if the condition is of the form A and B, then there could be a certainty factor for A and a certainty factor for B. The certainty factors of conditions are associated with facts held in working memory. Certainty factors for actions are stored as part of the rules.

Uncertainty in rules and user-supplied information is handled by many Expert Systems through the use of numerical certainty factors as indicated above. There are many approaches to handling uncertainty in knowledge representation such as probabilities, fuzzy set theory (Zadeh, 1976), Bayesian reasoning, the Dempster-Shafer theory of evidence, and certainty factors (Buchanan and Shortliffe, 1984) however; most expert systems assessment of uncertainty is based on the MYCIN certainty factors.

MYCIN certainty factors are based on the Stanford certainty theory, which is based on a number of observational data, (Lugar & Stubblefield, 1998). These include:

- In traditional probability theory the sum of the confidence for a relationship and confidence against the same relationship must add up to one, but this may not necessarily be true in real terms as an expert may have some confidence that a relationship is true and yet have no feeling of it not being true.
- The knowledge content of the rules is assumed to be of more significance than the algebra of confidences that holds the system together. This is because confidence measures correspond to the informal evaluations that human experts attach to their conclusions.

6.4.1 Combining Certainty Factors

Several rules can lead to the same conclusion or can be applied incrementally as new evidence become available to arrive at a conclusion on a ground improvement method. Thus, the rules for combining certainty factors are such that new evidence can be added to existing evidence. If the evidence is positive, this increases the certainty, as one would expect. But one never becomes 100% certain.

The rule for adding two positive certainty factors is to add one certainty factor with the other, the other having been reduced by an amount that depends on the size of the first:

Thus;

$$CF_{combine}\,(CF_A\ CF_B) = CF_A + CF_B\,(1 - CF_A) \qquad (6.1)$$

Where CF_A = certainty factor for condition A

CF_B = certainty factor for condition B

If A and B and C, the combined certainty factor (CF) is given by

$$CF = \min\,(CF_A, CF_B, CF_C) \qquad (6.2)$$

If A or B or C

$$CF = \max\,(CF_A, CF_B, CF_C) \qquad (6.3)$$

All positive evidence is combined to determine the measure of belief of a proposition and all negative evidence is combined to obtain a measure of disbelief. Only positive evidence which equate certainty factors with measures of belief were assumed relevant for this work.

Rules whose certainty falls below a certain threshold are deleted. For the purpose of this work a threshold of 20 was set. The reason for this cut-off value is because rules with certainty factors below and including 20 provide too weak evidence to support or deny a conclusion on a ground improvement method. The CF values can therefore be reduced by 20 without any significant effect in the results.

Assigning certainty factors to the various rules formulated to cover the ground improvement methods considered could not easily be accomplished as there was no other means of verifying statements or numeric values provided by each expert since each one of them was interviewed on different methods of improvement so as to be able to cover a good number of the numerous ground improvement technologies. In general, the experts frequently used descriptive terms such as common, uncommon, strongly suggestive and suggestive as the measure of belief in the factors they considered. Based on the above principle however, the approach adopted was to use certainty factors ranging from 0 to 100 (Table 6.18) as the factors considered have supportive evidence for a method selected. The certainty factors were then assigned to the rules in the ground improvement method selection knowledge base as a means of transforming the experts linguistic or imprecise terms that the conclusions made were valid into numeric values. Certainty factors ranging from 0 – 20 representing non-suggestive or slight hint conclusion were not considered important in the quantification. These factors were applied to the rules defined by the ***defrule construct*** (see section 6.5).

Expert linguistic term	Numeric equivalent
Very strongly suggestive	90-100
Strongly suggestive	80-90
Suggestive	60-80
Fairly suggestive	50-60
Weakly suggestive	40-50
Very weakly suggestive	20-40
Slight hint	0-20

Table 6.18: Numeric Interpretation of Expert Linguistic Terms

6.5 System Implementation

As stated in Section 5, the wxCLIPS shell was chosen for the implementation of the ground improvement decision support system. wxCLIPS which is a hybrid of the general CLIPS provides a modular, rule-based language, oriented to the incremental development of large and complex knowledge bases. Its inference engine has nonmonotonic reasoning capability. The modules are defined by the ***defmodule construct***, which allows partitioning of the knowledge base into other constructs such as ***deftemplate***, ***defrule*** and ***deffacts*** constructs which are described below. CLIPS modules allow a set of constructs to be grouped together such that explicit control can be maintained over restricting the access of the constructs by other modules.

The knowledge base is written in the form of facts and rules. The ***deffacts*** construct which has been extensively used allows a set of initial knowledge to be specified as a collection of facts. It therefore contains all the groups of facts that need to be considered during the decision-making process when considering the use of ground improvement technology. The construct contains all the facts concerning the various ground improvement methodologies. Those embodied in the construct include the loading condition, objectives of improvement, the ground conditions, environmental impact, economic considerations etc. under which the methods are applicable. The **deffacts construct** is represented as ***deffacts valid-combinations*** under the Initial Consideration caption and illustrated by the following.

The deffacts construct.

```
;;*************************
;;* INITIAL CONSIDERATIONS *
;;*************************
(deffacts valid-combinations ""
 (combine load)
 (combine improvement-objective)
 (combine ground-conditions)
 (combine site-conditions)
 (combine  construction-related-issues)
 (combine economic-considerations)
(combine environmental-impact)
(combine tradition)
(combine regional-practices)
(combine methods))
```

The ***deffacts valid-combinations*** construct allows the rules in the ***defrule constructs*** to match relevant facts in this construct. The method(s) selected for any one situation is a result of the combination of supportive evidence by various factors. Consequently, the *combine* command is utilized so as to account for all relevant factors.

The ***defrule*** construct is one of the primary methods of representing knowledge in wxCLIPS. A rule is a collection of conditions and actions to be taken if the conditions are met and therefore provides a modular way of representing reasoning knowledge. Rules fire based on the existence or non-existence of facts or instances of user-defined classes. In CLIPS (and all it's variants including wxCLIPS), rules are defined by the ***defrule*** construct. The construct consists of a Left-Hand Side (LHS), which is made up of a series of conditional elements (CE) consisting of pattern conditional elements to be matched against pattern entities and a Right-Hand Side (RHS) that contains a list of actions to be taken when the LHS of the rule is satisfied. The two sides are separated by an arrow (=>).

For the *defrule* constructs, three rule sets were formulated and to be executed in three phases namely the

a) choose qualities rule,
b) method selection rule and
c) the query rules

The object-attribute-value-triplet (OAV) approach was identified as a suitable format in presenting the rules. OAV triplets are particularly useful in representing facts and the patterns to the facts in the antecedent of a rule (Giarratano & Riley, 1998).

6.5.1 Choose Qualities Rule

Separate rule sets with the following distinctive features were written for each condition:

a) A confidence factor that indicates the reliability of the expert's conclusion; and
b) A form of weighting to show the relative importance of a condition in the premise.

These statements may be explained by means of the following examples.

Example 1.

```
(defrule choose-load-for-heavy-industrial-commercial-facility ""
  (phase choose-qualities)
  (facility industrial-commercial)
  (type heavy)
  =>
  (assert (load heavy 100 =(gensym))))
```

In this example, the left hand side (LHS) of the rule represented in the object-attribute-value-triplet (OAV) format is before the => symbol and the right hand side (RHS) is after this symbol. On the conclusion side, the figure 100 represents the confidence in the conclusion. This rule can be interpreted as follows:

If the facility is of heavy industrial/commercial type

Then there is 100% certainty the load is heavy.

The rule is assigned a unique tag by the function *gensym.*

Example 2.

```
(defrule choose-loading-for-medium-industrial-commercial-facility ""
 (phase choose-qualities)
 (facility industrial-commercial)
 (type medium)
 =>
 (assert (load heavy 70 =(gensym)))
 (assert (load moderate 90 =(gensym))))
```

This can be expressed as follows;

If the facility is of medium industrial/commercial type

Then there is 70% certainty the load is heavy,

and there is 90% certainty the load is moderate.

In this example the expert concludes that the load imposed by a medium industrial facility or commercial type facility is moderate with confidence of 90%. However, he has a confidence of 70% that load imposed by these same structures is heavy thus illustrating the relative importance of the condition in the premise.

6.5.2 The Method Selection Rules.

The selection of an improvement method is based on incremental evidence of support by the various independent rules that support the method. Consequently, wxCLIPS combines all the possible rules that fire whiles considering a particular method. To account for all the rules that apply to a method, the method selection rule covering each method consists of one large single rule containing all the various conditions. As an illustration, for the selection of the vibrocompaction method, wxCLIPS combines supportive evidence of type of load, objective(s) of improvement, ground-conditions. expertise-requirement and environment-associated factors among the numerous factors for the recommendation of this method of improvement. To represent this in wxCLIPS, the following ***defrule*** construct in the methods selection rules phase illustrates all the possible factors that would be taken into account if the vibrocompaction method were to be selected.

Example of the method selection rule

```
;************************
;;* METHOD SELECTION RULES *
;;************************
(defrule recommend-vibrocompaction ""
 (phase select-methods)
 (or (load light ?per1 ?)
    (load moderate ?per1 ?)
    (load heavy ?per1 ?))
(or (improvement-objective bearing-capacity-increase ?per2 ?)
    (improvement-objective settlement-control ?per2 ?)
    (improvement-objective liquefaction-resistance ?per2 ?))
   (ground-condition poor  ?per3 ?)
   (site-condition good ?per4 ?)
    (environmental-impact low ?per5 ?)
    =>
    (assert (method Vibrocompaction =(min ?per1 ?per2 ?per3 ?per4 ?per5)
=(gensym))))
```

This may be interpreted as follows:

IF the load is light or moderate or heavy and

the improvement objective is bearing-capacity-increase or settlement-control or liquefaction-resistance and

the ground-condition is poor and

the site-condition is good and

environmental-impact is low

THEN recommend Vibrocompaction method.

The **LHS** of the rule contains all the necessary conditions that must be met for the vibrocompaction method to be recommended. Many of the conditions in the premise are however made up of several sub conditions. For instance **environment-impact low** is arrived at upon consideration of sub conditions such as noise, ground-vibrations, groundwater-pollution and surface-water-pollution. For the environmental-impact to be assessed as low, it means that the method does not create undesirable noise levels, does not result in ground vibrations that may cause damage to existing facilities or create stability problems and does not result in high groundwater or surface water pollution levels.

The statement on the RHS of the rule:

(assert (method Vibrocompaction =(min ?per1 ?per2 ?per3 ?per4 ?per5) =(gensym))))

represents a choice that corresponds to a particular ground improvement method based on the conditions satisfied. In this case the vibrocompaction method is the choice. The certainty with which the method is selected is computed as explained earlier and displayed alongside the method. The rule is assigned a tag when it fires.

The reasoning model for the selection of an appropriate ground improvement methodology for an application is based on classification of the factors on the following levels of importance.

Firstly, reasoning based on the principal factors and secondly refinement of the initial conclusion through reasoning using secondary factors. To illustrate these levels of reasoning, suppose an improvement methodology is required for loose granular soil. wxCLIPS first selects some methods based on the major problem soil type (i.e. loose granular soil). In this case, methods such as vibrocompaction, dynamic compaction, compaction grouting, blasting and surface compaction which are suitable for densifying loose soils will be selected. It then further considers the selected methods based on secondary factors such as fines content, degree of saturation, depth of deposit etc. If the range of depth of deposit selected by the user for example is 0-3m, wxCLIPS recognizes this depth to represent shallow depth. As a result wxCLIPS will eliminate all the methods among these that are suitable for only deep seated formations such as vibrocompaction dynamic compaction and blasting. The focus will then be on the surface compaction and the compaction grouting methods which are applicable to the situation under consideration.

The inference engine always keeps track of the rules whose conditions have been satisfied.

6.5.3 The Query Rules

This was considered as a separate phase in the development of the knowledge based system. The rules in this phase were constructed for user input. For each rule, multiple-choice answers were provided from which the user is to select the most representative answer. If the user chooses conditions from those that are associated with a particular method of improvement, the system initiates the inference by asking questions that concern the condition but related to the method. For instance if the user selects a facility type building, wxCLIPS will then focus on questions relating to building such as whether the building is a low-rise residential facility, medium-rise residential facility or high-rise residential facility.

6.5.4 The Certainty Factor Rule

Since the selection of a method is based on multiple evidence of support by the factors, the general formula for positive or zero certainty factor was used for the calculation of the overall certainty factor for the method selected. wxCLIPS considers two certainty factors at a time and computes the combined certainty for the new combination after reducing the second by a factor as explained in Section 6.4. A new certainty is then computed. The new certainty factor is then combined with the certainty factor of the next rule fired and the combined certainty again determined. The procedure is repeated until the last rule met is fired. The overall certainty factor then represents the certainty factor with which the method under consideration has been selected. The ***defrule*** for the certainty rule is shown below.

```
;;****************************
;;* COMBINE CERTAINTIES RULE *
;;****************************
(defrule combine-certainties ""
  (declare (salience 10000))
  (combine ?rel)
  ?rem1 <- (method ?val ?per1 ?sym1)
  ?rem2 <- (method ?val ?per2 ?sym2&~?sym1)
  =>
  (retract ?rem1 ?rem2)
  (assert (method ?val
                =(/ (- (* 100 (+ ?per1 ?per2)) (* ?per1 ?per2)) 100) =(gensym))))
```

In the LHS, salience is a rule property allowing the user to assign a priority to a rule. Since there are multiple rules, the rule with the highest priority is fired first. Two rules, the first and second fired are stored in memory.

The RHS represents the formula for computing the certainty factor with which wxCLIPS arrives at selecting a method. The result is expressed in percentage. ***?val*** stands for the numerical value. The statement is interpreted as follows.

$$\text{Assert method with certainty factor} = \frac{100(CF1 + CF2) - CF1 * CF2}{100}$$

Where, CF1 and CF2 are the certainty factors of rules 1 and 2 fired respectively.

Following the MYCIN method of certainty factor determination, a cut off value of 20% was set as the minimum certainty value that should be reported for a method selected. This represents the worst scenario in which the method selected though could do the job would not be the most appropriate. The poor choices ***defrule*** shown below was therefore constructed to eliminate all poor choices.

```
;;*******************************
;;* ELIMINATE POOR CHOICES RULE *
;;*******************************
(defrule remove-poor-method-choices ""
 (phase remove-poor-choices)
 ?rem <- (method ? ?per ?)
 (test (< ?per 20))
 =>
 (retract ?rem))
```

Finally, after the selection of the methods, the print command enables wxCLIPS to out put the selected method(s) on screen. The following represents the print phase in the execution of rules.

```
;;***************************
;;* PRINT SELECTED METHOD RULES *
;;***************************
(defrule print-method ""
  (phase print-methods)
  ?rem <- (method ?name ?per ?)
  (not (method ?name1 ?per1&:(> ?per1 ?per) ?))
  =>
  (retract ?rem)
  (format t " %-24s %3d%%%n" ?name ?per))

(defrule end-spaces ""
  (phase print-methods)
  (not (method ? ? ?))
  =>
  (printout t t))
```

There are two rules in this phase. The first rule details the print format in which the name of the method and the computed certainty value are to be displayed in columns in the order of highest certainty value at top. The second rule is to create spaces thus separating the methods output for legibility.

6.6 Conclusion

The building of a decision support system for ground improvement method selection using knowledge–based system approach has been presented. Two knowledge bases namely the soil characterization and ground evaluation knowledge base and the ground improvement method selection knowledge base have been described. Both the rule base and procedural approaches were used in the development of the two knowledge bases.

The soil characterization and ground evaluation knowledge-base is used to identify the soil formations underlying the project site and then it evaluates the need for ground improvement based on the types of soil. In the method selection knowledge base the various factors that are considered vital for the selection of a suitable ground improvement method for a project are described. The selection of an appropriate method for the project is based on input data from the user. All the applicable methods are shown.

Because ground improvement, like many other practical tasks requires reasoning under uncertainty, certainty factors were introduced in the method selection knowledge base in order to deal with any inexactness, missing and inconsistencies in the knowledge gathered. The system therefore attaches certainty factors to each method selected as a measure of the confidence with which it was selected.

CHAPTER 7

VALIDATION OF SYSTEM AND DISCUSSION

7.1 Introduction

An important aspect in the development of a knowledge-based system is evaluation of the system. The evaluation process consists of two components namely verification and validation (usually referred to as V & V process) to which the knowledge–based system must be subjected before it can be accepted into real-world critical applications. These are reliability assessment of the knowledge-based system's inference quality. The two processes are necessary in order to determine the dependability of a knowledge-based system. A knowledge-based system is of little use if it does not function properly.

As the number of rules in the knowledge-based system increases, the number of possible interactions between the rules increases rapidly. The critical factor to focus on is ensuring that the knowledge base provides an acceptable answer to every query.

Validation is to determine if the 'right' system was built (O'Keefe & O'Leary, 1993; Tsai et al., 1999), where as verification determines if the system was built 'right' (Lockwood & Chen, 1995; Owoc et al., 1999). One can therefore think of verification as ensuring that the knowledge is collected and structured properly, while validation ensures the knowledge produces correct results (Santos Jr. et al., 1997). The two are accomplished through testing. The validation process should be carried out at the same time as the knowledge acquisition and both must be incremental (Lockwood & Chen, 1995). According to Owoc et al., 1999, the validation process in practice involves two kinds of tasks namely:

a) Activities that intend to reach the structural correctness of the knowledge base (verification).
b) Activities that intend to demonstrate the knowledge base ability to reach correct conclusions (evaluation).

They indicate that the validation can be conducted on different components of the knowledge-based system such as the knowledge base, the inference engine or even a user interface to mention a few.

In order to validate the knowledge base, the different methods that could be applied to achieve the goals of the above activities are shown in Fig 7.1.

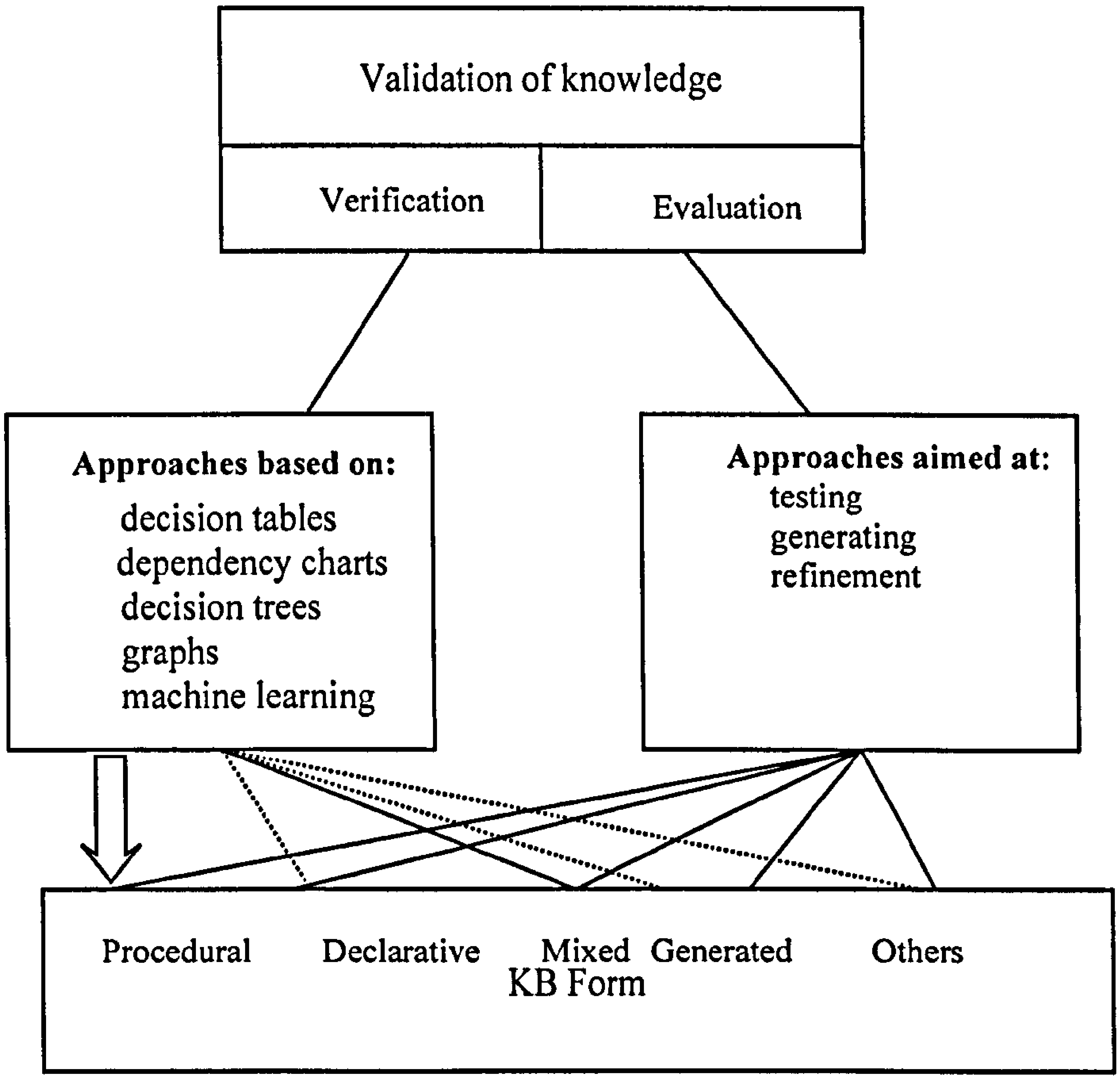

Figure 7.1: Approaches used in Knowledge Validation (after Owoc. et al.,1999)

Verification of the knowledge base can be accomplished by the transformation of the knowledge base into decision tables, decision trees, some graphical forms or by activation machine learning techniques. The transformed bases are then subjected to completeness and consistency tests.

The main activity in the evaluation procedure is testing, which is usually conducted to ensure that the knowledge base has the ability to reach correct conclusions. Testing is usually carried out by comparing the system performance with that of human expert documented in test cases.

Two approaches for the V & V proposed by Lockwood & Chen (1995) are:

a) the knowledge engineer considers the knowledge-based system as a whole or
b) he studies the different parts of the KBS and the behaviour of this set of parts.

Ideally any rule base knowledge-based system is built with the view to ascertain that the system acts like

a) some particular expert(s)
b) the knowledge contained in the knowledge base should faithfully represent the actual knowledge of the domain expert(s)
c) the experts understanding of the domain.

This does not happen whenever the knowledge acquisition process fails to correctly capture experts' intent or whenever the acquisition does not capture all that the expert knows. Then, an inaccurate knowledge base results. The knowledge validation process therefore deals with inaccurate and incomplete knowledge. It is therefore recommended that the V & V should be conducted from the very beginning of the knowledge system design and should be started at the knowledge level.

Verification

This is concerned with consistency, completeness and conformance to methodology (Lockwood & Chen, 1995; Spreeuwenberg & Gerrits, 1999). In knowledge-based systems, the knowledge engineer validates rules. The requirement of any rule base includes the following:

a) consistency
b) rules must be reachable and cycles eliminated
c) rules must not be redundant or display subsumption.

In order to accomplish these requirements the following techniques are used:

a) consistency is verified by a demonstration that for all inputs, the knowledge base produces a consistent set of conclusions i.e. that for each set of possible inputs, all the conclusions can be true at the same time.
b) to verify completeness one must demonstrate that for all inputs, the knowledge base produces some conclusion. Questions however arise as to how to achieve this as such an exercise depends on the extent to which the knowledge about the domain had been collected (May et al.,1997)
c) a knowledge base is redundant when the same knowledge is represented in different places or there exists knowledge, which does not contribute to the output of the system (but can in fact be true knowledge).

The standard list of errors (Gonzalez & Dankel, 1993) against which rule-bases are to be checked in the verification process includes the following:

a) Redundant rules: rules that have the same conditions and conclusions.
b) Conflicting rules: rules that use the same or very similar conditions, but result in different conclusions.
c) Subsumed rules: rule or rule-set meaning expressed in another rule that reaches the same conclusion from similar but less restrictive conditions.
d) Circular rules: rules that lead back to an initial or intermediate condition instead of a conclusion.
e) Unnecessary **IF** conditions: the value on a condition does not affect the conclusion of any rule.
f) Dead-end rules: values of a condition that are outside the acceptable set of values for that condition.
g) Missing rules: values on a condition that are not defined; consequently their occurrence cannot result in a conclusion.
h) Unreachable rules: rules that do not connect input conditions with output conclusions.

There are two areas the expert system developer should take note of in the verification & validation process, which are peculiar to expert systems: inconsistencies and incompleteness. Inconsistencies can be caused by redundant rules, conflicting rules, subsumed rules, unnecessary premise clauses, and circular rule chains. Incompleteness can be caused by unachievable antecedents or consequences and unreferenced or illegal values.

In this chapter, a description of the verification and validation processes is presented. The verification process is discussed in Section 7.1. The validation of the system is described in section 7.3. Seven case studies have been presented in the validation process. This is followed by a discussion in section 7.4. The chapter is completed with the conclusions drawn in Section 7.5.

7.2 System Verification

In order to achieve completeness and consistency in the ground improvement knowledge-base system a verification process was carried out using the tools provided by the wxCLIPS shell. One important tool within wxCLIPS that was found to be useful for this purpose is the **watch** tool. When turned on, it allows the developer to observe the facts that are being asserted and also the rules being fired. In general, the **watch** command allows the tracing facilities of **CLIPS** to be activated. The possible **watch** items that are activated include: **facts, rules, activations, focus, compilations, statistics** and **globals,** any one of which the developer can select at a time or the **watch all** command when all the items are to be traced.

By activating **watch facts,** all fact assertions and retractions are displayed. If **rules** are watched, all rule firings will be displayed. The **watch** tool was therefore used extensively in the checking process in both of the knowledge bases namely: the soil characterization and ground evaluation knowledge base and the method selection knowledge base, to ascertain whether the rules in each of these knowledge bases fire correctly. This was carried out by inputting facts relating to the rules whiles running the system and monitoring the output results.

It is important to state that some of the aforementioned irregularities could not easily be detected whilst developing the system. For instance, where redundant rules were present it was difficult to locate the exact problem even though wxCLIPS would register an error message.

7.3 System Validation

In order to ensure that the right system was developed, it became necessary to conduct a validation process with the view of ascertaining this fact once the system was fully developed. As stated in Section 7.0, validation of the knowledge-based system can take many forms. This could be the knowledge base, the inference engine or the user interface. Since **GriMSA** is developed to assist the geotechnical engineer in the selection of an appropriate method when faced with construction or development on problematic soils, it was thought that the validation process would be concentrated on the knowledge base. The common approach for the validation of a knowledge-based system is by the use of the "Black box" technique as cited by Coenen & Bench-Capon (1993). The "Black box" testing technique involves input and output only whereby appropriate input data is provided and then the output is examined so as to test the knowledge base. A successful test is one with a correct output. To achieve this, test cases are usually resorted to.

The validation of **GrIMSA** was conducted by the use of 7 case studies, obtained from the literature, of projects that have been carried out in different countries using different ground improvement techniques. The projects studied (Table7.1) vary in nature from simple structures such as buildings to more complex ones such as tunnels, and were chosen in order to determine if the knowledge–based system could be applied to a diverse range of facilities and different conditions.

Case Study	Facility	Location	Soil type(s)	Method applied	Reference
1	Prestressed concrete water tank	Los Angeles, U.S.A	soft clay fill, dense & firm alluvium, bedrock	stone columns	Davis and Roux (1997)
2	Yaoqiang Int. Airport runway	Jinan, China	silty sand, silty clay, silt and clay, soft clay	vacuum preloading	Tang and Shang (2000)
3	Shopping center	Mendota Wisconsin, U.S.A	peat, organic silty clay, medium sand	preloading	Edil (1983)
4	Breakwaters	Zeebrugge, Belgium	loose sands and soft clays	soil replacement	De Wolf et al., (1983)
5	Office building	Bonn, Germany	granular fill, loose, medium, dense sand, sandy gravels, gravels	jet grouting	Bell (1993)
6	Tunnel, shaft	Milwaukee, Wisconsin, USA	glacial till, fill soils, sands and clayey silts	ground freezing	Sopko and Andersland, 1998
7	Medium rise building	Florida, U.S.A	loose-very loose silty sand, fine sand, seams of sandy clay	dynamic compaction	FHWA (1995)

Table 7.1: List of Projects.

For each case study, the information included data relating to the site characterization (where possible) following site investigation programmes and the general project site description. The ground improvement method(s) applied to each case is stated. Factors that were considered in the selection of each method by the project executors are also listed where possible.

Case Study 1

Davis and Roux (1997) describe a case study where stone columns have been used for controlling differential settlement beneath a 3.785 x 10^7 litre (10-million gallon) prestressed concrete water tank in Los Angeles, California. Details of the project are as follows:

Site description

The site is located within the Los Angeles Department of Water and Power's (LADWAP) Rowena Reservoir property, 6.4 km north-northwest of the centre of downtown Los Angeles. The Rowena Tank was to replace the Rowena Reservoir, which was removed from service in March 1992 due to embankment stability problems.

A thorough site investigation of the tank site consisting of subsurface investigations in 1992 and 1993 and a review of bore logs and laboratory test results of earlier investigations in 1968, 1969 and 1985 revealed the following stratigraphic relations from top to bottom:

1) Dark brown soft clay fill generally composed of moist and soft, light to dark brown or grey, sandy silty clay with minor small –sized gravel. It ranges from about 4.88m to 10m thick.
2) Moderately dense and firm alluvium comprising of brown, sandy, silty clay and light brown, clayey sandy silt.
3) Highly weathered, soft and compressible consisting mainly reddish brown to grey claystone bedrock (referred to as BR1 i.e. Bedrock 1).
4) Non-weathered and non-compressible reddish brown to grey claystone (BR2).
5) Very hard, dense and dry dark grey to black claystone and siltstone (BR3).

Groundwater was observed to flow through the rock.

The material properties of these zones based on soil tests conducted in accordance with ASTM are presented in Table 7.2. In column 3 of the table, the alluvium and BR1 are combined to form a single zone due to the similarity in their strength and consolidation characteristics.

Material Property	Fill	Alluvium and BR1	BR2	BR3
γ_d (kN/m^3)	15	16.5	16.5	17.8
w_n (%)	24.2	20.0	20.0	15.0
Ø′ (degrees)	12	28	25	36
c′ (kPa)	19.15	12	16.76	19.15
I_p (%)	34	27	23	14
k (cm/sec)	-	4 x 10^{-08}	2 x 10^{-08}	2 x 10^{-09}
C_c	-	-0.1042	-0.074	-
C_r	-	-0.0300	-0.014	-
OCR	-	1.0-9.5	1.0-5.1	-

Table 7.2: Geotechnical Properties of Soils and Bedrock at Rowena Tank Site (after Davis and Roux, 1997).

Notes: γ_d =field dry unit weight; w_n = field moisture content; Ø′ = effective internal friction angle; c′ = effective cohesion; I_p = plasticity index; k = permeability; C_c = virgin compression curve slope; C_r = rebound curve slope for one-dimensional consolidation; OCR = Over Consolidation Ratio.

The conventional one-dimensional consolidation theory was used for settlement analysis of the tank. The results indicated a maximum expected settlement of 26.7cm and the maximum differential slope below the tank to be 0.62% near the edge of the tank. Bell, (1978), Bowles, (1988) and Das, (1990) recommend the maximum differential slope for structural buildings should be limited to 1/500 or 0.2% if cracking is not allowed and this was adopted as the differential slope criterion for the tank. Since the calculated maximum differential slope of 0.62% exceeds the selected criterion, foundation improvement was found necessary in order to successfully implement the project.

Several foundation improvement alternatives were considered. Among them are: deep dynamic compaction, vibro-compaction, lime columns, surcharging, permeation grouting, jet grouting, compaction grouting, remove and recompact, driven pile and grade beams and stone columns. Some of the factors that were considered in making a decision on an appropriate method from the aforementioned methods are shown in Table 7.3.

Alternative	Method of application	Practicality of application at tank site	Estimated cost* ($m)	Reference
Deep dynamic compaction	compaction by dropping heavy weight	not effective in cohesive soils. Impact shocks could disturb neighbours.	NA	Esrig, et al. (1991)
Vibro-compaction	densification	not effective in cohesive soils	NA	GKN H. Baker Inc. (1993)
Lime columns	soil mixing/ reinforcing	limited use in the USA	4	Broms (1984)
Surcharging	preconsolidate soil	time to achieve ultimate settlement exceeded allowed construction schedule	NA	
Permeation grouting	alter physical characteristics by grout injection	not suitable for fine grained soils at this site	NA	Fang (1991)
Jet grouting	replacement	costly	>>4	Fang (1991)
Compaction grouting	displacement/soil densification with pressurized, low slump grout	costly	4.5	Fang (1991)
Remove and recompact	engineered fill	dewatering difficult. effective strength of saturated clay could not support equipment	7	Davis et al. (1994)
Driven piles and grade beams	bypass weak soils with structural system	costly	8	
Drilled piles and grade beams	bypass weak soils with structural system	costly	10	
Stone columns	vibro-replacement	selected	1.7	Priebe (1976)

Table 7.3: Foundation Alternatives Investigated for Rowena Tank (after Davis and Roux 1997).

Note: * = total project cost including foundation improvement and associated site work.

NA = Not Applicable

The stone columns alternative was selected based on several factors including:

a) Soil type.

b) Cost.

c) Constructability.

d) Availability of expertise.

e) Regional practices.

f) Time.

The Knowledge-Based System Recommendation

In order to determine an appropriate method of ground improvement for the poor foundation soils that underlie the project site, the information relating to the soil characteristics and the relevant available information regarding the Rowena Tank site that influence the choice of method were input into GrIMSA and the output examined.

There is insufficient information on the soil properties, given in Table 7.2 that could be used in classifying the underlying soils based on the USCS. It was therefore necessary to use the descriptions of the soils as provided above. Based on the shear strength properties c′ and Ø′ from Table 7.2, the shear strength of the top soil was calculated to be 42.8kN/m^2. Table 7.4 shows the properties of the soil that were used for the classification of the soil. In the table, some of the soil properties are given a range of values.

Soil property	Determined value	Input value	Remark
Plasticity index I_p	34	>30	Highly plastic
strength kN/m^2(estimated)	42.8	25 – 50	Soft clay
Unit weight γ_d (kN/m^3)	15	15	Low density

Table 7.4: Input Values of Soil Parameters.

The user selects the range of values which best describes the soil property under consideration. Based on these properties and an assumption that the soil is fine grained, the knowledge-based system identified the soil as soft clay rather than an artificial soil. The soil is known to be fill material.

In order to identify the most appropriate method or methods of ground improvement that could be used for the improvement of the soil, several factors ranging from ground conditions to economic considerations were entered into GrIMSA. The input data are as follows:

1) soil-type
    - soft clay

- alluvium (cohesive soil)

2) depth-range-of-soil-deposit
    - greater than 3m
3) facility-type: tanks/towers
4) improvement-objective
    - settlement control
    - bearing capacity increase
    - lateral stability
5) environmental-impact

    The environmental factors such as high noise level, pollution of ground and surface waters and high vibration levels were considered. Since there is no indication of existing structures, surface streams or water bodies near the site it was assumed that there would be no adverse environmental impact due to construction activities at the site. Therefore the input environmental impact factor in GrIMSA is low.
6) construction- related-issues
    - Because of the nature of the facility, some appropriate levels of expertise and labour skills may be required to conduct what ever method of ground improvement that will be used. Highly skilled labour together with high expertise or averagely skilled labour with available expertise to put in place what ever method that is considered appropriate might be appropriate. Consequently, for expertise requirement, and labour requirement, the input parameters are yes and labour skilled respectively.
    - Methods that would improve the soil at a very short interval were considered most appropriate. Therefore, immediate improvement was selected.
    - For construction materials availability the attribute unknown was input as no information on this factor is available.
    - Equipment availability was also considered as a prominent determining factor for which ever method that is considered appropriate. The input value was yes.
7) In terms of construction-budget the input parameters were low and moderate. These two were considered so that the cost of construction would not exceed the construction budget even though no details of the available funds were provided.
8) Regional-practices: this was not considered as a very important determining factor even though the condition exists.

Based on the above input parameters a set of methods have been recommended by GrIMSA. The suggested methods for improvement of the top layer and the alluvium materials that have been output are shown below. The certainty with which each method is selected rounded to the nearest whole number is displayed alongside the method.

SELECTED METHODS (Soft Clay)

METHOD	CERTAINTY
Stone-Columns	99%
Vacuum-Consolidation	99%
Lime-Columns	99%
Micropiles	99%
Fracture-Grouting	95%
Fiber-Reinforcement	84%
Electroheating	76%

SELECTED METHODS (Alluvium and BR1)

METHOD	CERTAINTY
Stone-Columns	99%
Micropiles	99%
Fracture-Grouting	99%
Vacuum-Consolidation	99%
Lime-Columns	99%
Fiber-Reinforcement	84%
Electroheating	76%

Five methods namely, stone columns, micropiles, fracture grouting, vacuum consolidation and lime columns have been consistently output with a certainty of 99% as appropriate methods for the improvement of the foundation soil of the project under consideration. The indication is that any of these five methods could be used for the improvement of the underlying soft soil layer and the alluvium and BR1. Included in the suggested methods is the method that was adopted for the execution of the project. Micropiles are generally used for the underpinning of existing structures particularly buildings. The method can also be used for new facilities so the selection of this method for the Rowena concrete water tank should not be seen as inappropriate. Since the same methods have been recommended for both soil layers (soft clay layer and alluvium and BR1) the use of a single method for the improvement of the two soil layers will yield appropriate results.

The results show some similarity with the methods that were initially considered in the real case.

Case Study 2

Tang and Shang (2000) presented the use of vacuum preloading consolidation technique for the improvement of poor soils underlying the Yaoqiang International Airport runway, between 1990 and1991. The airport runway, which measures 2600m long and 60m wide, is located in the city of Jinan, China.

The area is underlain by alternate layers of silty sand, silty clay, silt and clay with an approximately 4m thick under-consolidated soft clay layer occurring at depths of between 7.5m and 11.5m. Underlying this soft clay layer is a silty clay layer that extends to a depth of 20m. The stratigraphic relations and the soil properties at the site obtained from averages of 54 boreholes along the runway are summarized in Table 7.5. The soil classification is based on the Chinese soil classification system.

Description	Depth (m)	Engineering properties				
		w %	γ kN/m^3	e	c_v cm^2/s	k cm/s
Silty sand	0 - 3	12-18	15.6-19.0	0.83-0.98	-	2.80×10^{-2}
Silty clay	3 - 5	26-31	19.0-19.5	0.85-0.88	0.042	1.87×10^{-5}
Silt	5 - 7.5	28-32	19.0-19.2	0.73-0.81	0.035	7.85×10^{-5}
Soft clay	7.5 -11.5	32-40	17.2-19.2	1.10-1.60	0.001*	1.55×10^{-6}*
Silty clay	11.5 - 20	22-28	19.3-20.3	0.60-0.70	0.021	2.00×10^{-5}

Table 7.5: Soil Profile and Properties at Yaoqiang Airport Runway (after Tang & Shang 2000).

Notes: Silty sand: 50% by weight exceeds a particle size of 0.0075mm.

Silty clay: the plasticity index is greater than 10 but not more than 17.

Silt: the plasticity index is greater than 3 but not more than 10.

Soft clay; the plasticity index is greater than 17, the natural water content is greater than the liquid limit and the void ratio is greater than 1.0

c_v and k values obtained from standard consolidation tests.

*: Estimated.

Elevation of ground surface = +21.3m to +22.2m.

Elevation of ground water table = +19.1m.

Based on the site soil properties, it was thought that excessive settlement would be induced by both the static and dynamic loading of the runway. As a consequence, soil improvement at the site was proposed so as to consolidate the site prior to construction. Two ground improvement techniques namely, vacuum preloading consolidation and surcharge preloading techniques were considered. Similar improvement results were obtained from the two methods from pilot test programmes. The vacuum technique was however chosen as the most appropriate method based on the following factors:

a) No fill materials required.
b) Shorter treatment time.
c) Availability of expertise and skilled labour.
d) Regional practices.

The Knowledge-Based System Recommendation

Because there are different layers of soil underlying the project area it was decided that the selection of an improvement technique should be carried out for each layer of soil as the thicknesses of these formations are quite substantial. In order to identify the soil layers, the soils grain sizes were assumed based on the descriptions provided, as silt, silty sand silty clay and soft clay. The silty sand layer has high permeability. From the C_v values and the soil void ratios, the soils characterization and ground evaluation knowledge base predicts the soft clay layer will undergo settlement and consequently ground improvement was suggested.

In order to suggest an appropriate method of improvement for the subsurface materials, the following input parameters were used in GrIMSA.

1) soil-type.

- silty sand
- silt
- soft clay
- silty clay

2) improvement-objective

- bearing capacity increase
- settlement control
- liquefaction control
- seepage control

3) depth-range-of-soil-deposit

- <3m
- >3m

4) facility-type

- embankment

5) ground-conditions

- stratigraphy: stratified
- layer thickness: thick
- layer uniformity: lateral-uniform
- groundwater-regime: unknown

6) environmental-impact low

- parameters input for this factor are low noise level, low vibration and low pollution levels. These were selected because of the effect that high noise level and high ground vibration level would have on other existing structures and the users of the airport.

7) construction-related-issues

- construction materials availability : unknown
- haulage distance of available construction materials: economic
- construction equipment availability: unknown
- both immediate and long-term improvement time schedules were considered.

8) construction-budget (a low construction cost was considered due to size of project)
9) site-conditions (generally site restraints)

- site size was considered as large
- site accessibility was considered as accessible
- for site development the input parameter was developed
- proximity of developments :remote

10) regional practices: the input attribute was unimportant since the methods that have been preferentially used in some regions has not been firmly established.

From the above considerations the following methods were output as the suggested appropriate methods for the improvement of the various layers.

For the topmost silty sand layer, surface compaction, lime stabilization, cement stabilization, remove and replace and the mechanical stabilization methods have been output with certainties of 99%. The electroheating method was selected with the least certainty factor of 50%.

SELECTED METHODS (silty sand layer 0-3m)

METHOD	CERTAINTY
surface-Compaction	99%
Lime-stabilization	99%
Cement-stabilization	99%
Remove-and-Replace	99%
Mechanical-Stabilization	99%
Geotextile	75%
Fiber-Reinforcement	75%
Electroheating	50%

The methods suggested for the layers below 3m are shown below

SELECTED METHODS

METHOD	CERTAINTY
Dynamic-Compaction	99%
Preloading	99%
Lime-Columns	99%
Remove-and-Replace	99%
Vacuum-Consolidation	99%
Fiber-Reinforcement	75%
Electroheating	50%

For the formations at depths below 3m the system has suggested dynamic compaction, preloading, lime columns remove and replace, and vacuum consolidation with certainties of 99%. The electroheating and fibre reinforcement methods have also been suggested but with lower certainty values of 75% and 50% respectively. The selection of the remove and replace method as a deep ground improvement method for the construction of the air port runway may be inappropriate due to the problem of disposal of large quantities of waste material. In addition to this problem, there will also be the problem of increased cost as the disposal program will escalate the overall cost of construction of the project.

Both vacuum consolidation and the preloading techniques have been suggested as appropriate methods for the improvement of the soils at deeper levels. These are in line with the initial proposals of the consultant.

For the surface deposits any of the methods with higher certainty factors could be employed to improve the properties of the soil. The surface compaction method could be applied to the top silty sand layer and subsequently followed up with the any of the suggested deep improvement techniques for the improvement of the underlying layers.

Case Study 3

In case study 3, Edil, (1983) describes the use of the preloading technique to improve a 4m thick peat deposit to serve as the foundation of a shopping centre near Lake Mendota in Middleton, Wisconsin, U.S.A between 1976 and 1977.

General Description

The proposed building was a one-storey shopping centre covering an area of about 4.240m^2. The structure consisted of a flexible steel frame with the maximum column load on the order of 310kN. The columns were to be supported on square footings 1.8 x 1.8m and 150mm thick concrete floor slab was to be poured on the grade. A uniformly distributed building load of 12kPa was assumed for the purpose of settlement analysis.

Site Investigation

Subsurface exploration programmes involving the sinking of 36 borings supplemented by soundings revealed the following stratigraphy at the site with the youngest at top.

a) a black, brown very fibrous peat of a maximum thickness of 4m
b) grey organic silty clay of about 3.7m thick
c) grey and tan fine to medium sand with relative density of firm to very firm.

Groundwater level coincides with the ground surface.

Properties of the Soils

The average engineering properties of the peat are presented in Table 7.6.

Description	Average value
Water content, w_n (%)	510
Unit weight, (kN/m^3)	9.1
Specific gravity, Gs	1.41
Vane shear strength kPa	7.0
Sensitivity S_s	22.0
Ash content (%)	12.0
Fiber content (%)	64

Table 7.6: Average Engineering Properties of the Lake Mendota Peat (after Edil, 1983).

The one-dimensional consolidation test on the grey organic silty clay yielded the following average consolidation parameters for stress increment of 25 to 100kPa:

Coefficient of consolidation = 53m^2/day
Secondary compressibility = 8.4 x 10^{-3}
Volume compressibility = 6.3 x 10^{-4}m^2/kN
Average water content = 51%
Unit weight = 15.9kN/m^3

Settlement analysis of the soils indicates a total settlement of 1.13m under the final building load over a period of 30 years.

Construction Considerations

Three construction options for the foundation were considered namely:

a) Excavation of organic materials and replacement with an appropriate firm material compacted in place.
b) Use of 25m piles for the transfer of the column loads to the very firm stratum and to carry the structural floor slabs.
c) Removal of 1m of the peat to be replaced with 4.6m high fill to surcharge the compressible layers.

The third option was selected based on the following considerations:

a) Sufficient time was available for consolidation of the compressible layers before construction work for the project began.

b) Considerably low overall cost.

c) The first option would involve the removal and disposal of about 33000m^3 volume of material - an expensive venture.

d) The second option would also involve a high cost due to the requirement of a structural floor to transmit the floor loads onto the column caps.

The Knowledge-Based System Recommendation

The parameters used for the identification of the peaty layer are shown in Table 7.7

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Property	Input value
Grain size	Not applicable
Water content	Very high (above 100%)
Compressibility	Highly compressible
Sensitivity	Quick clays (Skempton and Northey 1952)
Fiber content	>50%

Table 7.7: Input Parameters for Identification of Lake Mendota Peat Layer.

The most important parameters used in the identification of the peat are its high fibre content, water content and sensitivity. The layer is therefore thought to be sensitive and would pose settlement problems to the proposed facility.

In order to select an appropriate ground improvement methodology for improving the properties of the peat, the input parameters include the following:

a) soil-type
   - peat

b) improvement-objective
   - bearing capacity increase
   - settlement control
   - lateral stability increase

c) facility-type
   - industrial/commercial (low-rise)

d) geology

- uniform
- non-stratified
- thickness: thick

e) environmental-impact

- due to the presence of the lake in the area it is thought that there maybe pollution of surface waters close to the site hence low pollution was input.
- to avoid groundwater pollution the pollution level considered is low.
- low noise level was input with the view that the shopping center might be located near a built-up residential area though this has not been stated.
- low vibration level was also considered with the view that adjacent structures would not be adversely affected.

f) construction-related-issues

- construction materials requirement : for availability of construction materials the input attribute is unknown as information about this is not given.
- construction equipment availability : available.
- material durability : durable
- expertise requirement :high
- labour: skilled
- time schedule: tight, non-tight.

g) construction-budget (a low construction budget was considered)

h) construction-site-restraints: low; this comprises of

- headroom availability
- no surface or subsurface developments
- accessibility: accessible

i) regional-practices

- regional preferences in the use of the methods to be selected was not considered important hence for this parameter the input data was unimportant

The suggested methods together with the certainty with which each method is selected are shown below.

SELECTED METHODS

METHOD	CERTAINTY
Lime-Columns	99%
Preloading	99%
Micropiles	99%
Fiber-Reinforcement	99%
Vacuum-Consolidation	97%

The preloading technique, which was the method used for the project in addition to lime columns, micropiles, fiber reinforcement and vacuum consolidation have been suggested by GrIMSA for the improvement of the foundation soil properties. Each of the above methods could be applied for the improvement of the underlying peat layers. Even though lime columns have been suggested the use of this method in the US is limited. The fiber reinforcement method is particularly used for stability purposes especially for cut slopes. This method could probably be used in combination with other methods.

Case study 4

De Wolf et al., (1983) describe the use of the soil replacement method for the construction of the new outer harbour at Zeebrugge, Belgium.

Project Description

The Belgium Government decided in 1976 to extend the then existing port of Zeebrugge and to construct a new outer harbour located in the Schedt estuary. Two types of breakwaters namely sandasphalt mound breakwaters and rubble-mound breakwaters measuring about 3.5km were built into the North Sea. Sandasphalt type of breakwater was used for the service port while the rubble-mound type was used for the outer harbour breakwaters. The outer breakwaters consist mainly of :

a) the foundation and bottom protection works,

b) the breakwater core (random rubble 2-300kg) protected on the harbour side by a cover of quarry stone grade 1-3 tons and on the seaside by a filter layer of quarry stone of the same grade and an armour-revetment of concrete cubes of 25 tons,
c) the crest with a service road,
d) the toe protection consisting of willow mattresses and quarry stone berms of weight 3-6 tons at the seaside and 1-3 tons at the harbour side.

Soil Profile

An extensive site investigation programme consisting of continuous seismic profiling, CPT tests and boring and laboratory testing revealed the area is underlain by heterogeneous quaternary deposits of loose sands and soft clays to a depth of about 4 to 6m underneath the seabed overlying a medium dense to dense sand layer. At the base is a stiff tertiary clay layer known as the Barton clay. The dense sand layer may be absent in places. CPT test results indicated the soft clay and loose sand layer cone resistance was less than 1.5MN/m^2. The bearing capacity of the surface layers was found to be insufficient to construct the breakwaters directly on the natural soil layers over much of the entire length of the breakwaters.

Based on technical and economic considerations a soil replacement procedure was resorted to over large lengths of the breakwaters where the bearing capacity was insufficient. This was accomplished by the removal of the top loose sands and soft clays by the use of large seagoing cutter suction dredgers and hopper suction dredgers and replacement with relatively coarse sea sand won in the existing and future navigation channels to the harbour. CPT test were carried out after the replacement exercise. The CPT values which ranged between 6 and 10MN/m^2 or even more indicated a significant increase.

The Knowledge-Based System Recommendation

The parameters input for the selection of an appropriate method of ground improvement for the structures include the following

1) soil-type
    - loose granular soil
    - soft clay
2) improvement-objective
    - bearing capacity increase

- settlement control
- lateral stability
- liquefaction control

2) facility-type
   - because the structure is a breakwater which is not catered for in GrIMSA, it was thought appropriate to select a structure that may be in close relation to this. As a result the input structure was Bridge-abutment.
3) environmental-impact
   - low (as construction work is to be conducted in a water body the method applied should be such that the water pollution level is maintained as low as possible.
   - noise: low
4) construction-budget
   - a low construction budget was considered appropriate
5) construction-related-issues
   - because the facility is a specialized facility there is the need to use a method with expertise available. Expertise requirement input is high.
   - labour: skilled
   - there must also be suitable equipment for the construction work
   - accessibility to the site must be adequate
6) regional-practices was not considered as an important factor since a restriction on this may result in the project been abandoned.

The methods that have been selected for the improvement of the loose sandy layer and output by GrIMSA are shown below

SELECTED METHODS (loose sand)

METHOD	CERTAINTY
surface-Compaction	99%
Remove-and-Replace	99%
Lime-stabilization	99%
Biotechnical-Stabilization	99%
Fracture-Grouting	99%
Geotextile	99%
Cement-stabilization	97%
Electroheating	96%
Mechanical-Stabilization	84%

The location of and nature of the project makes the selection of many of the methods such as biotechnical stabilization, cement stabilization, lime stabilization, electroheating and surface compaction very questionable. The biotechnical stabilization method for instance involves the use of live plants. This may not be possible under water. Both the cement and lime stabilization methods require the mixing of the poor soil with cement or lime. The recommended procedures for these methods have stipulated limited amounts of soil moisture, so that their use below a water body would be likely to be inappropriate.

For the soft clay layer the methods suggested are shown below

SELECTED METHODS

METHOD	CERTAINTY
Micropiles	99%
Fracture-Grouting	99%
Remove-and-Replace	99%
Lime-Columns	99%
Fiber-Reinforcement	84%
Electroheating	60%

The methods which are highly recommended are micropiles, fracture grouting, remove and replace and lime columns. Both the remove and replace and fracture grouting methods have been suggested for the treatment of the two soil layers. Fracture grouting may be considered a very expensive venture as compared to the replacement method and consequently the most appropriate method may be the replacement method.

Case study 5

Bell (1993) presents a case application of the jet grouting method for the improvement of poor foundation soils at the site for the construction of the Deutscher Herold Building in Bonn, Germany. The building was to house new computer facilities. Because of the need for additional floor space, the construction of a basement was found necessary to provide this additional space.

Site Description

The site is located in a built-up city centre environment surrounded on three sides by existing four and five storey buildings whose stability could be affected due to the construction of the basement.

Soil Profile

The area is underlain by the Rhine Terrace deposits with the following stratigraphy (Table 7.8). The groundwater level was at 8.2m, which was 5.2m above the proposed final excavation level.

Depth below ground surface (m)	Description
0 - 2	Fill (mainly granular)
2 - 7	Loose to medium dense sands
7 - 18	Medium dense sandy gravels and gravels
Below 18	Tertiary clays

Table 7.8: The Rhine Terrace Deposits at Deutscher Herold Building Site.

Improvement Method Selection.

Based on several technical considerations such as the type of soil, groundwater level, lack of space on the built-up sides of the excavation, restrictions on pollution of groundwater and cost, Keller Grundbau proposed the use of the jet grouting technique for the improvement of the soils. Triple jet grouting was conducted to form soilcrete columns which interlocked the full length of the underpinned section and extended down through the sands and gravels into the impermeable tertiary clays. The columns were formed using cement grout of water : cement ratio of 0.7. A structural diaphragm wall was constructed on the fourth side of the site where there were no buildings and therefore did not require underpinning.

The Knowledge-Based System Recommendation

Because the properties of the underlying soils have not been provided the descriptions of the soils have been taken as given. Consequently the soils are identified as granular fill (artificial material), loose sands, medium dense sands, medium dense sandy gravels and gravels. Based on the density descriptive terms loose and medium that have been used it is suspected that the soils may have low bearing capacities and therefore will have poor to good value for foundation. Therefore the foundation soils may require some improvement to be suitable for the location of the proposed structure at the site.

The input parameters are as follows

a) soil-type

- granular fill (artificial soil)
- loose sand
- medium sand
- medium sandy gravel
- medium gravel

b) depth-range-of-soil-deposit
- shallow
- deep

c) facility-type
- medium-rise building (based on the nature of the surrounding buildings)

d) site-condition
- high site restraints due to existing structures (buildings)
- accessibility (site is suspected to be accessible due to its location)
- stability (unknown)
- topography (unknown)

e) environmental-impact
- high (groundwater pollution, effect of vibrations on other buildings, effect of noise on the community)

f) construction-related-issues
- expertise-requirement : high
- labour-requirement : skilled

Based on the above input parameters, the recommended methods output by GrIMSA are shown below. Several ground improvement techniques have been suggested for the improvement of the granular fill layer with certainties ranging from 84% to 99%. The methods with the highest certainty include ground freezing, jet grouting, micropiles, lightweight fill, mechanical stabilization, biotechnical stabilization and electro-osmosis. The methods output with the highest certainty of 99% for the sand and gravel zone include ground freezing, jet grouting, stone columns and micropiles. For the two layers under consideration the jet grouting method which was the one used for the execution of the project has been selected with a certainty of 99% thus ranking among the top ones.

SELECTED METHODS (granular fill layer)

METHOD	CERTAINTY
Ground-Freezing	99%
Jet-Grouting	99%
Micropiles	99%
Lightweight-Fill	99%
Biotechnical-Stabilization	99%
Mechanical-Stabilization	99%
Electro-Osmosis	99%
Soil-Anchoring	97%
Lime-stabilization	97%
Cement-stabilization	97%
Lime-Columns	97%
Fracture-Grouting	96%
Electroheating	96%
Fiber-Reinforcement	93%
Soil-Nailing	84%

SELECTED METHODS (sand and gravel zone)

METHOD	CERTAINTY
Ground-Freezing	99%
Jet-Grouting	99%
Stone-Columns	99%
Micropiles	99%
Deep-Soil-Mixing	97%
Lime-Columns	97%
Fracture-Grouting	96%
Electroheating	96%
Electro-Osmosis	90%
Soil-Nailing	84%

Case study 6

This case study is concerned with the application of the ground freezing technique to develop a frozen earth wall system for the support of structures designed to transfer storm water runoff from surface collector systems to deep large diameter tunnels in the Milwaukee, Wisconsin area, USA. The construction site measuring 4.8ha is located on the south bank of the Menomonee River in proximity to the Menomonee and Milwaukee River junction. The use of slurry diaphragm walls in the earlier stages of the shaft construction was unsuccessful due to failures. Consequently the ground freezing techniques was chosen as an appropriate construction technique.

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The frozen earth wall system selected included a deep shaft and three adjacent cells, two elliptical and one circular in cross-section. The dropshaft with an internal diameter of 5.64m, extended down through water bearing soils and another 35m of rock.

Soil Profile

Analysis of boring logs carried out at the site indicates the area is underlain mostly by glacial till. No consistent soil stratification was evident, however the till was composed of a clay matrix with varying quantities of silt, sand, gravel and boulders. The generalized boring profile is presented in Table 7.8

Strata	Depth (m)	Description
I	0.0 – 4.0	Fill soils, sands and clayey silts
II	4.0 – 18.3	Post glacial estuarine silts
III	18.3 – 21.3	Glacial silty sand-clay mixtures
IV	21.3 – 33.5	Glacial lacustrine sands
V	33.5 – 38.1	Lacustrine sands and silts
VI	38.1 – 50.6	Top of rock
	50.6	Bedrock

Table 7.9: Generalized Soil Profile at Menomonee River Project Site (after Sopko and Andersland, http://www.groundfreezing.com/frozen_earth_cofferdam_design.html).

The Knowledge-Based System Recommendation

The properties of the soils that are necessary for the classification of each layer of soil are not known. As a result it is not possible to input any data into GrIMSA for the identification of the soils. Since the two components of GrIMSA are independent the available data could still be fed into GrIMSA for the selection of an appropriate method of ground improvement.

The following input parameters were used in order to suggest an improvement method for the underlying soils at the site.

1) soil-type (generally mixed soils)
    - the upper 4m was regarded as consisting of sand and cohesive clays
    - soil layer II was considered as a fine grained soil generally silt

- layer III was considered as a mixed soil.
- layers IV and V were considered as sand

2) improvement-objective.
   - The sandy layers were considered as soils that would pose stability problems, seepage problems , and bearing capacity problems
   - Settlement was regarded as the most important problem that would be posed by the cohesive materials silt and clay.
   - Because the bulk of the materials are composed of silts and sands the ground may also undergo liquefaction should ground vibration levels exceed the thresh-hold. As a result liquefaction control was considered.
3) facility-type: tunnel, shaft
4) geology
   - stratified
   - layer uniformity: variable
   - layer thickness: variable
5) environmental-impact
   - The structure is located at the bank of the Menomonee River. As a result of this location the methods that would be found appropriate for the improvement of the soils should be those that would not result in any pollution of the surface waters. Input parameter for pollution is low.
   - The presence of the sand layers could pose seepage problems which could pollute the groundwater. Consequently any method under consideration should be one that would not result in groundwater pollution. Therefore the input parameter for groundwater pollution is low.
   - The overall input parameter for environmental impact is low
6) construction-related-issues: the input parameters include
   - expertise: high
   - labour: skilled
   - construction equipment: available
   - construction materials: available, unavailable, unknown
   - construction time schedule : tight

     this value was input due to the presence of high ground water levels at the site so that the method to be considered should result in the immediate improvement of the soils.

7) site-restraints: both low and high site restraints were entered because of the location of the site and nature of project. Since the facility is a tunnel there may be several restraints including headroom availability, buried utilities, and transportation of equipment to some sections of the tunnel.

8) economic-considerations
   - To account for cost considerations, two cost estimates high and moderate were entered in order to consider high and moderate construction budget respectively.

The following show the output of GrIMSA indicating the most appropriate methods suggested for the project.

SELECTED METHODS (upper 0-3m sand layer)

METHOD	CERTAINTY
Ground-Freezing	100%
Mechanical-Stabilization	99%
Fiber-Reinforcement	99%
Lime-stabilization	99%
Cement-stabilization	99%
Geotextile	97%
Fracture-Grouting	95%
Electroheating	87%

SELECTED METHODS (lower glacial till layers)

METHOD	CERTAINTY
Ground-Freezing	100%
Stone-Columns	99%
Jet-Grouting	99%
Compaction-Grouting	99%
Lime-Columns	99%
Micropiles	99%
Permeation-Grouting	99%
Deep-Soil-Mixing	99%
Vibrocompaction	99%
Fiber-Reinforcement	99%
Electro-Osmosis	99%
Fracture-Grouting	95%
Electroheating	87%

The method output in GrIMSA with the highest certainty of 100% for the surface layers is ground freezing. The other methods considered next to this are the mechanical, cement and lime stabilization and fiber-reinforcement methods with certainties of 99%. For the glacial till layers below 3m, several methods have been output. The one with the highest certainty is the ground freezing method with a certainty of 100%. A variety of methods from traditional stone columns through grouting to electrical methods have been suggested. The most likely reason for this large number could be the type of soil input for this section of the soil profile. The section has been represented by the soil type mixed.

Case study 7

FHWA (1995) described a case study of the densification of loose soil pockets and voids in an area demarcated for the location of a three-storey building in Florida, U.S.A. The initial site investigation reports indicated the presence of sinkholes and voids as a result of the dissolution of limestone formations and a heterogeneous soil profile with large predicted differential settlements.

The subsurface materials are predominantly variable thicknesses of loose to very loose silty fine sands grading to fine sand with seams of sandy clay. These soils have low SPT N-values ranging between 1 and 4. Other soil types are the dense varieties of these soils due to cementation resulting from the presence of the calcareous materials which are interbedded with the loose sands. The SPT N-values for such materials are above 25. These differences indicated the foundation support would range from very good load support on the cemented materials to very poor load support on the loose materials and in the cavernous areas.

Settlements ranging from 23mm to 74mm were predicted from the initial soil profile assuming no large collapse of voids was to occur. This indicated the structure would be subjected to a differential settlement of 51mm which was considered too large for the structure.

As a result of the low bearing capacity and high differential settlement, the designer suggested the use of shallow foundations on a more homogeneous load support material with no voids present within the depth range of 7.6m to 9.1m below ground surface.

The dynamic compaction method was selected for this project based on the following factors:

a) Soil type which is predominantly a loose silty sand formation.
b) Availability of a local contractor.
c) Availability of equipment {the contractor had a 15Mg tamper which could produce enough energy to improve the soil to the design depth of improvement of 7.6m (see section 2.4.1) by applying the energy in two phases}.
d) Availability of expertise (the local contractor was a specialist dynamic compaction contractor).

The Knowledge-Based System Recommendation

The ground improvement method adopted as the most suitable method for improving the loose soils at the site for the location of the three-story building in Florida, U.S.A. was tested with GrIMSA to ascertain its suitability as a decision support tool for ground improvement method selection.

The following are the input data.

1) soil-type :
    - loose silty sand
    - loose sandy clay
    - dense silty sand
    - dense sandy clay
2) facility-type: medium-rise residential building
3) improvement-objective
    - bearing capacity increase
    - lateral stability increase
    - settlement control
4) geology
    - stratification: stratified
    - layer thickness: variable
    - layer uniformity: homogeneous
5) environmental-impact :low
    - low construction noise effect
    - low construction vibration effect to adjacent structures

- low pollution of surface and ground water if any

6) site-restraints
    - site size : unknown
    - site accessibility: accessible (assumed)
    - surface developments: no
    - subsurface developments: no
    - site: open
    - accessibility: accessible
7) construction-related-issues
    - construction materials availability: unknown
    - construction equipment availability: available
    - expertise: available
    - labour: skilled
8) regional-practices : consider
9) construction-budget: low

The following outputs represent the lists of methods that have been suggested as the appropriate ground improvement techniques which could be used for the improvement of the foundation soil.

SELECTED METHODS (loose silty sand layer)

METHOD	CERTAINTY
Dynamic-Compaction	100%
Lime-Columns	99%
Soil-Nailing	99%
Soil-Anchoring	99%
Deep-Soil-Mixing	99%
Fracture-Grouting	97%

Dynamic compaction has been recommended with a 100% certainty. The other soil improvement techniques apart from fracture grouting have been suggested with a certainty of 99%. Any of the above methods could be used for the improvement of the loose silty sand.

7.4 Discussion

The validation of **GrIMSA** has been conducted by the use of seven case studies on existing facilities in different parts of the world.

Results from the seven case studies above have demonstrated the ability of **GrIMSA** to assist the engineer during the selection of a method of ground improvement for construction purposes. For each case study a limited number of methods have been suggested as appropriate ground improvement methodology that could be used for the improvement of the foundation soils. Each of the methods on the lists is assigned a certainty factor which represents the confidence with which the method has been selected from among the 32 methods that are represented in **GrIMSA**. The certainty values for the methods selected for the cases that have been investigated are very close or equal to each other. All methods with the same certainty suggest there is no much discrimination in the confidence with which each is selected and the appropriateness of each for the project. Included in the list of methods output for each case is the method that was used for the improvement of the foundation soil. Apart from two case studies, (case study 6 and case study 7), where the suggested method with the highest certainty factor is clearly distinguished as the most appropriate method and which coincides with the real case method used, there is no clear cut distinction between the method used and the other methods suggested by **GrIMSA**.

The limited number of methods output narrows down the number of methods the engineer will consider therefore saving him time. The display of very close or equal certainty factors also leaves the final choice of the method to use to be made by the engineer based on his/her judgement and this gives him/her a series of practical options.

Where more than one layer of soil exists, each significant layer will have to be treated as a distinctive stratum of soil. This implies that in situations where there is vertical variation in the composition of the soils or strata, many more different methods maybe suggested. This may compound the problem of selecting a single appropriate method or a composite of methods. It has been observed that where there is significant differences in the soils types when different soil layers occur, some methods are or a method is found to recur in the **GrIMSA** output for the different layers (see case study 6). Under such circumstances one of the methods that are found to recur could be selected as the most appropriate single technique for treating the underlying problematic soils. It is however considered that some refinement in **GrIMSA** may be possible to narrow down the list of methods output.

It is also important to state that for each of the above case studies approximations had to be made in making a choice on the attributes for the most representative value. However, even so the results are appropriate.

7.5 Conclusions

The validation of **GrIMSA** has been conducted with seven case studies. For each case the list of suggested methods includes the method that was applied during the execution of the project. Even though the method used in the real case may not stand out with the highest certainty factor in the **GrIMSA** output, it is almost certainly one of the appropriate suggested methods.

The results indicate that **GrIMSA** could be used as an assistant in the initial decision making process. By so doing the list of methods to consider is shorter thereby giving the engineer or consultant a better focus in addition to saving time.

The final choice of the method to use is made by the engineer. The output of a series of methods gives him/her a series of practical options to make from based on his own judgement.

CHAPTER 8

CONCLUSIONS

8.1 Conclusions

Ground improvement technology is usually resorted to at a given site as a construction alternative only when there is evidence of poor quality foundation material(s), usually described as problematic soils. The poor quality may be due to unsatisfactory properties that may not meet engineering standards or requirements for the project to be executed on these soils. The problems encountered on problematic soils during and after construction of the intended facility are poor stability, low bearing capacity, excessive or uncontrolled settlement and also seepage.

Ground improvement is one of the special construction options for problematic soils and has been used over the years to modify the engineering properties of such soils for engineering purposes. The methods of ground improvement that could be used to solve the above problems are many and may be soil dependent. Some new methods are still evolving. The selection and execution of a method of ground improvement requires some expert advice due to the complex nature of the ground. However, there are only a small number of ground improvement experts within the geotechnical community.

A prototype decision support system, **GrIMSA** has been compiled to assist the geotechnical engineer and in particular ground improvement decision makers when making a choice of ground improvement technology. The major objectives were to develop a system to cover most of the traditional methods of ground improvement and one which could assist the ground improvement specialist in the selection of appropriate methods of ground improvement to solve foundation problems in or on problematic soils.

GrIMSA contains knowledge gathered from numerous sources of literature and ground improvement experts, thus making it an invaluable source of information for practicing ground improvement engineers. A number of publications were reviewed and the relevant information from them was compiled. The information so obtained was combined with that from the ground improvement experts and converted into rules for the decision support tool.

The various techniques used for the acquisition of knowledge from the ground improvement domain experts for the construction of the decision support tool have been described. The procedure involved the use of questionnaires and interviews. The use of the open questionnaire format which allows good sampling of the views of domain experts did not however prove to be the most appropriate approach for knowledge elicitation in the ground improvement domain. This conclusion has been arrived at mainly because about 60% of the questions set in this format were left unanswered by most of the experts who responded to the questionnaire. This could be attributed to the lack of time available for such extra work within their usually tight schedules.

Each problematic soil has certain unique properties that could be used to identify it. The characteristics of the problematic soils stored in the knowledge base of the system have therefore been presented. Due to significant differences in the Codes of Practice and Standards for testing geotechnical materials adopted in many countries or regions of the world, there are no unique values of these soil parameters. The most appropriate approach was to use reasonable ranges of values to represent most of the soil characteristics.

The reasons for which a ground improvement method may be considered to be the most appropriate for a particular project are numerous therefore making the selection criterion cumbersome. The use of decision tables has been found to be an appropriate representation for the relevant conditions.

The system has been developed using the expert system shell wxCLIPS which is a variant of NASA's CLIPS. It consists of two knowledge bases namely the soil characterization and ground evaluation knowledge base and the ground improvement method selection knowledge base. Results from the soil characterization knowledge base can be used as facts for rules in the ground improvement method selection knowledge base; however the ground improvement method selection knowledge base can function independently when limited information is available for the proper execution of the soil characterization knowledge base. The soil characterization knowledge base can be used as a stand alone system.

Validation of the system was carried out using seven case studies, obtained from the literature, of projects executed in the USA, Belgium, Germany and China. The system suggested a limited number of ground improvement methods that were considered appropriate for the execution of each project. For each test case the suggested methods included the one adopted for execution of the project with high confidence even with limited input data. This is a measure of the accuracy of **GrIMSA.**

The selection of a limited number of methods offers the decision maker a choice on the most appropriate method(s) for the project using his/her engineering judgement thereby fulfilling one of the objectives of the system development as an assistant and not to replace the expert.

Even though **GrIMSA** could serve as a valuable source of information, it has one drawback in that it is impossible to ensure that it contains all the knowledge about ground improvement in its knowledge base for three reasons namely:

a) The multiplicity of ground improvement methods.
b) The continuous modification of some of the existing methods.
c) The rapid development of new techniques.

The system can however be modified to accommodate additional data about new or existing methods as it becomes available.

CHAPTER 9

RECOMMENDATIONS

9.1 Future work

Following the performance of the prototype decision support system as described within this thesis, the following recommendations for future work are been made.

The current **GrIMSA** output suggests a number of ground improvement methods that could appropriately be used for a project under consideration; however, there is no significant distinction between the suggested methods because of the similarity in the certainty with which they are suggested. Such an output will make it difficult for the user to make a choice, thereby, not contributing very meaningfully to the decision making process. It is thought that the cost model adopted for the development of **GrIMSA** does not explicitly distinguish between the methods within **GrIMSA** and may be a contributory factor to the current output. The current model which is based on broad ranges of relative cost of site treatment lacks any information on mobilization/demobilization costs for the various methods under consideration even though this condition exists. Combining this information with other cost factors would allow the system to clearly distinguish the economic aspects of each of the methods to consider. Therefore, modification of the cost model to include this factor of cost for each of the methods covered in **GrIMSA** may be an area for future development. It is envisaged that such an approach would clearly distinguish between the certainties with which the various methods are suggested for the system to be useful to the consultant.

There are many ground improvement methods and new ones are still evolving. Even the traditional methods, for which sufficient knowledge is known, are still being modified to suit current day project requirements. It was therefore impossible to include all the conditions for which any one method could be selected for a particular project in the current prototype decision support system. The system can be expanded to include further information as it becomes available.

The allocation of certainty factors to the rules could not be fully verified. The usability of the system will depend on the confidence with which the methods are suggested. Therefore there is potential to further verification of the system.

Only a few case studies have been used for the validation of the prototype decision support system. An expansion of the validation process to include a wide variety of projects is being recommended in order to test the versatility of **GrIMSA.**

The current system does not include information on the design of the methods for ground improvement. For example if the dynamic compaction method is suggested, further advice may be needed as to the grid pattern including the separation of compaction points. The inclusion of such details would enhance the performance of **GrIMSA** and also assist the decision maker in the design process. This would be likely to further encourage the use of the system by ground improvement experts.

Significant differences which exist in the preferred usage of some of the ground improvement methods throughout the world have been identified. For example, the lime columns method is not popular among ground improvement specialists in the U.S.A. This will be due partly to lack of technical know-how, although of course some of these differences may be due to lack of knowledge/experience of the system. Establishment of and inclusion of any regional or national trends in the use of the ground improvement methods may need to be conducted in order that the system can be used worldwide.

APPENDIX A

GROUND IMPROVEMENT METHODS SURVEY

This survey is being carried out to obtain adequate information on ground improvement techniques that are in use today.

The following are a number of questions/information relating to ground improvement practices. I would be grateful if you could spare a bit of your precious time to complete the questionnaire. Some of the questions in this survey can be answered with just a tick of a box. The answers to a number of the questions can be picked from Q1 by indicating the itemized number where appropriate. Spaces provided are for further information. Please use additional sheets where more space is required.

The information you provide will be used for a research programme being carried out for the development of a knowledge-based system for ground improvement as part of a PhD project.

Your participation and assistance is highly appreciated.

Please enter your name and address

....

Organization

....

....

Major functions

Consultant ☐

Contractor (general) ☐

Contractor (specialty) ☐

Other ....

PART 1

Q1. The following are some of the conventional ground improvement technologies in use today. Which of these methods have you or your organization used before or intends to use? Please mark the appropriate box (es).

Category A

1) Dynamic compaction ☐

2) Vibrocompaction ☐

3) Vibro-replacement ☐

4) Preloading/ Surcharge ☐

5) Blasting ☐

6) Heating ☐

7) Stone and Lime Columns ☐

8) Freezing ☐

9) Electro-osmosis ☐

10) Drainage ☐

11) Vibro Displacement ☐

12) Vacuum Consolidation ☐

Category B

13) Reinforcement Soil Steel ☐

14) Fibre reinforcement ☐

15) Geosynthetics ☐

16) Soil nailing ☐

17) Mechanically stabilized earth structures ☐

18) Natural reinforcement ☐

19) Micro piles ☐

20) Soil and Rock Anchors ☐

Category C

21) Compaction Grouting ☐

22) Jet grouting ☐

23) Permeation grouting ☐

24) Hydrofracture grouting ☐

25) Compensation grouting ☐

26) Fissure grouting ☐

27) Bulk grouting ☐

29) Deep soil mixing ☐

30) Shallow soil mixing ☐

Category D

Other innovative methods. Please specify

Q2. For what types of structures have you used or intend to use the method(s) ticked in Q1?

a) Multi-storey buildings ☐

b) Low rise buildings ☐

c) Bridge foundations ☐

d) Embankments ☐

e) Tank farms ☐

f) Water ways ☐

g) Ware houses ☐

h) Tunnels ☐

i) Slopes ☐

j) Excavations ☐

k) Industrial facilities ☐

l) Containment structures ☐

m) Walls ☐

n) Other (please indicate) ....

Q3. What other types of structures in your opinion can these methods be applied to?

....

Q4. Which of the above methods would you recommend for the improvement of the following? Please pick from 1 – 30 in Q1.

a) soft clay.....................

b) expansive soil ....

c) collapsible soil ....

d) liquefiable soil ....

e) organic soil/peat...........

f) frost susceptible soil......

Q5. What factors influence your choice of method? Please tick as many as applicable.

a) Cost ☐

b) Quality of workmen ☐

c) Popularity of method ☐

d) Time ☐

e) Availability of materials ☐

f) Availability of equipment ☐

g) Size of project ☐

h) Well defined theoretical basis ☐

I) Nature and type of structure ☐

j) Accessibility of site ☐

k) Project location ☐

l) Project life span ☐

m) Availability of expertise ☐

n) ground conditions ☐

Please indicate any other factors that may not have been included above.

....

Q6. How often do you use the method(s) chosen in question 4 above in your locality?

a) Frequently ☐ b) Quite frequently ☐ c) Occasionally ☐ d) Other (please specify method) ....

Q7. a) For what types of structures do you often apply the methods indicated in Q4? (Please indicate the structures under the methods you used or would use)

....

b). Which other types of civil engineering facility could these methods be used for. (Please indicate the facilities under method)

....

Q8. Which of the methods in Q1 are suitable for only temporary ground improvement works. (Please indicate only itemized number)

....

Q9. From the ground improvement techniques known to you, which method(s) is/are most unreliable in achieving performance objectives/ target specifications?

....

Q10. Which methods (show only itemized number) yield best results (or are reliable) in meeting target specifications for

a) Multi-storey buildings
b) Road embankments/Dams
c)Shallow foundations/Housing projects
d) Industrial Facilities
e) Walls
f) Water ways
g) Bridge foundations/ abutments
h) Excavations
I) Containment structures
j) Ware houses

Q11. What peculiar characteristics of the soil result in the variation of choice of method of improvement?

....

Q12. Which method(s) would you recommend for the following situations

a) Mitigating effects of excessive deformation or differential settlement

b) Increase resistance to deformation ....

c) Reduce settlement ....

d) Improve stability of slopes ....

e) Stabilize foundation ground ....

f) Reduce movement due to seismic activity ....

Q13. On a scale of 1 to 10 where 1 is of least importance and 10 the greatest, how would you describe the role of ground water in the decision making process?

a) 1-2 ☐ b) 2 - 4 ☐ c) 4 - 6 ☐ d) 6 – 8 ☐ e) 8 - 10 ☐

Q14. (a) Which method(s) would you recommend for the improvement of soils above the groundwater table? ....

(b) Which method(s) would you recommend for the improvement of soils below the groundwater table? ....

(c) For situations with fluctuating groundwater levels (seasonal, tidal or otherwise) which method(s) would be most applicable? ....

Q15. a) Has environmental impact any influence on choice of method?

a) Yes ☐ b) No ☐

b) If yes is your answer to question 15, in what form?

a) Land degradation	☐	d) Instability	☐
b) Pollution/contamination	☐	e) Effect on existing structures	☐
c) Noise	☐	f) Other (please specify)	

c) If you have ticked more than one answer please arrange them in order of importance.

....

Q16. Which of the methods listed in Q1 above may cause some environmental concerns in terms of

a) Land degradation ....

b) Pollution/contamination .....

c) Noise..................................

d) Instability.............................

e) Effect on existing structures.   f) Other (please specify)

Q17.If a method would have any adverse effects on existing facilities, what minimum distance of clearance would you recommend as safe. (Please list method and the corresponding safe distance).

Method	Safe distance (m)
....	....

Q18. What factors would determine the safe clearance distance?

a) Method of application ☐   c) Function of existing facility ☐

b) Nature of existing facility ☐   d) Other (please specify) ....

Q19. Which methods do you consider in terms of relative cost in general terms as

a) high to very high cost............   d) moderate cost........................

b) high cost...............................   e) Low to moderate cost...........

c) Moderate to high cost............   f) low cost ....

Q20. Please indicate (US$ or £ Sterling) what relative cost figures in terms of treated area you would describe as

a) Low cost .... b) Moderate ..... c) High ....d) Very High...........

Q21. In your opinion, do you think the use of composite methods can significantly reduce cost? a) Yes ☐ b) No ☐

Q22. Please list the methods that can be used in

a) Constrained and or built up sites.   b) Large, open, undeveloped sites

....

Q23.Which methods are suitable for

a) Remedial works only   b) proposed new facilities

....

Q24. i). Does thickness of soil stratum influence type of improvement method?

a) Yes ☐ b) No ☐

ii) If you have answered yes to Q24 what minimum thickness of poor soil stratum should necessitate an improvement or treatment strategy for

a) Light load structures?

a) 1m ☐ b) 1.5 m ☐ c) 2m ☐ d) 5m ☐ e) other (Please specify)

....

b) Heavy load structures

a) 1m ☐ b) 1.5 m ☐ c) 2m ☐ d) 5m ☐ e) other (Please specify)

....

Q25. What is the minimum thickness of soil stratum that you would recommend the use of ground improvement? ....

Q26. Please list the methods you would recommend for improvement at the following depths

a) Shallow depths (< 3m)	b) Moderate depths (3-10m)	c)Deep depths (>10m)
....	....	....

Q27. Depending on type of facility what maximum depth of occurrence of poor soil stratum from surface should call for ground improvement strategies for long term load intensity for the following:

a) Light loaded foundations

i) 5m ☐ ii) 10m☐ iii) 15m ☐ iv) other (please specify ....

b) Medium loaded foundations

i) 10m ☐ ii) 15m ☐ iii) 20m ☐ iv) other ......

c) Heavy loaded foundations

i) 15m ☐ ii) 20m☐ iii) 25m ☐ iv) 30m ☐ v) other...............

d) Heavy loaded floors

i) 5m ☐ ii) 10m ☐ iii) 15m ☐ iv) other (please specify ....

Q28. What loads (please indicate units) would you classify for foundations and floors as

	Foundations	Floors
Light.	....	....
Moderate	....	....
Heavy	....	....

Q29. What design life would ground improvement projects normally be envisaged?

a) 1- 5 years ☐ d) 25 – 50 years ☐

b) 5- 15 years ☐ e) 50 – 100 years ☐

c) 15 – 25 years☐ f) > 100 years ☐

Q30. i) Are there any contractual requirements that may limit the use of some ground improvement methods? a) Yes ☐ b) No ☐

ii) If yes please list ....

Q31. What proportion of the existing ground improvement techniques would you think are carried out by specialist contractors only?

a) > 10 % ☐ d) 30 - 40% ☐

b) 10 – 20 % ☐ e) above 40 % ☐

c) 20 - 30% ☐ f) other(please specify)............

Q32. Do effects of natural hazards play a role in the selection of a ground improvement method? a) Yes ☐ b) No ☐

Q33. In localities with good record of absence of natural hazards, should consideration of such effects play any important role?

a) yes, marginally ☐ c) yes, highly ☐

b) yes, significantly ☐ d) not necessary ☐

Q34. How would you describe the influence of politics (national, local government or otherwise) on the decision process?

a) High ☐ e) Not applicable ☐

b) Very significant ☐ f) Other (please specify) ....

c) Significant ☐

d) Not significant ☐

Q35. Please list the methods that are most suitable for

a) small scale projects ....

b) medium scale projects...................................

c) large scale projects.....................................

APPENDIX A

GROUND IMPROVEMENT METHODS SURVEY: PART 2

This section deals with the individual Methods of Ground Improvement Listed in Part 1 and others which may have been omitted.

Q1. Please indicate one method listed in Part 1, Q1 that you are more familiar with (use separate forms if more than one method).......

Q2. Which types of soil is this method applicable to...

Q3. Are there any peculiar soil characteristics that may influence the effectiveness of the method? Please list them.

....

Q4. What types of application is this method most suitable for? Please select from the list below.

a) Reduce settlement	☐	d)Increase liquefaction resistance	☐
b) Improve Bearing Capacity	☐	e) Improve seepage barrier	☐
c) Densification of soil	☐	d) Other (please specify)	

Q5. Is this method of ground improvement in popular use in your locality?

a) Yes ☐ b) No ☐

Q6.a) If you have answered yes to Q5, please state any reasons that have contributed to its popular usage.

....

b) Give reasons for which you personally would prefer to use this method.

....

Q7 a) Are there any limitations on size of area to be treated?

a)Yes ☐ b)No ☐

b) If yes what are the minimum and maximum sizes of area that the method can be applied to. Please state area in m^2.

a) minimum size (m^2) .... b) maximum size (m^2)..............

Q8 What maximum depth of improved ground can be achieved by this method? Please state. Maximum depth of treatment. (m) ....

Q9. What is the minimum thickness of poor soil layer that in your opinion you think this method could be recommended for use? ....

Q10. Is the method suitable for the treatment of built-up areas? Yes...... No.........

Q11. Is the method suitable for the treatment of areas with obstacles such as buried utility lines? a)Yes ☐ b)No ☐

Q12. Is the method suitable for the treatment of areas with obstacles such as surface utility lines? a)Yes ☐ b)No ☐

Q13. Can the method be applied in areas with low headroom? a)Yes ☐ b)No ☐

Q14. a) Does the method require the use of foreign materials for the construction work?

a) Yes ☐ b) No ☐

b) If yes, what type of materials? ....

Q15 What haulage distance would you describe as economic for the transportation of materials?

a)< 5km ☐ d)16-20km ☐
b) 6-10km ☐ e) up to 30km ☐
c) 11-15km ☐ f) other (please specify).............

Q16.a) Are there any environmental concerns that the use of this method may raise?

a)Yes ☐ b) No ☐

Q17. Which of the following environmental issues may be associated with the method?

a) Noise ☐ d) Groundwater pollution ☐
b) Stability ☐ e) Surface water pollution☐
c) Ground vibrations ☐ f) Dust ☐

Q18. Which of these cost categories would you assign to the method?

a) low cost ☐ b) moderate ☐ c) high cost ☐

Q19. What average cost per meter of treated ground do you think this method would entail? Please indicate in GBP or US$...................

Q20. Please indicate the mobilization cost if any of this method in GBP or US $ ....

Q21. In your opinion are there any climatic barriers to the use of the method?

a)Yes ☐ b)No ☐

Please state reason...................................

Q22 In which of the following areas would you recommend the use of this method for the treatment of soil

a) above groundwater table ☐ b) below groundwater table ☐ c)both regions ☐

Q23. Which of the following saturation states is the method applicable to? (Select as many as applicable)

a) dry soil ☐ b)saturated soil ☐ c) partially saturated soil ☐

Q24. Does the use of this method require the presence of an expert at site all the time?

a)Yes ☐ b)No ☐

Q25 The method can be applied successfully by the use of

a) skilled labour only

b) both skilled labour and experts

c) unskilled labour and expert

Q26 List the advantages that you would associate with this method?

....

Q27. List the disadvantages that you would associate with this method

....

Q28. Please state the factors that you would consider if you are to recommend the use of this method for the improvement of a particular ground condition.

....

Q29. Is this method suitable for application in a built up environment?

a)Yes ☐ b)No ☐

Q30. If yes what should be the maximum clearance from the closest structure? Please state ....m

Q31. If no, please state reason ....

Q32. What effects has the method on the adjacent ground ....

Q33. What are the consequent effects on existing structures if the method has any effects on the adjacent ground?

....

Q34. In your opinion are there any climatic barriers to the use of the method?

a) Yes ☐ b) No ☐

Q35. If there are any climatic barriers please indicate these.

....

APPENDIX B

Parameter Assessment Methods

Factor	Parameter	Assessment	Purpose
Soil/rock parameter	classification a) plasticity	Atterberg limits visual classification CPT classification Charts	slope stability, bearing capacity, settlement
	b) grain size distribution	visual classification CPT classification Charts particle size analysis	slope stability, bearing capacity, settlement, liquefaction
	soil state parameter a) unit weight/density b) void ratio	correlate with SPT, CPT, index properties, shear wave velocity	slope stability, bearing capacity, settlement
	c) relative density		slope stability, bearing capacity, settlement, liquefaction
	d) consolidation history		slope stability, bearing capacity, settlement
	strength parameters a) undrained strength	vane shear test, CU test, correlations with CPT, SPT, index properties	slope stability, bearing capacity, settlement
	b) drained strength	CD tests, CU tests with pore pressure measurement, correlations with index properties, CPT and SPT.	slope stability, bearing capacity, settlement
	fill compaction characteristics	laboratory compaction tests	stability, bearing capacity
	permeability	laboratory or field tests	seepage
	liquefiable layer thickness	soil borings or CPT soundings	liquefaction
Slope	grade and geometry	construction plans, field reconnaissance	slope stability, liquefaction
Static loading	structural loads hydraulic loads soil loads surcharge loads	from design engineer or plans and specifications	slope stability, bearing capacity, settlement

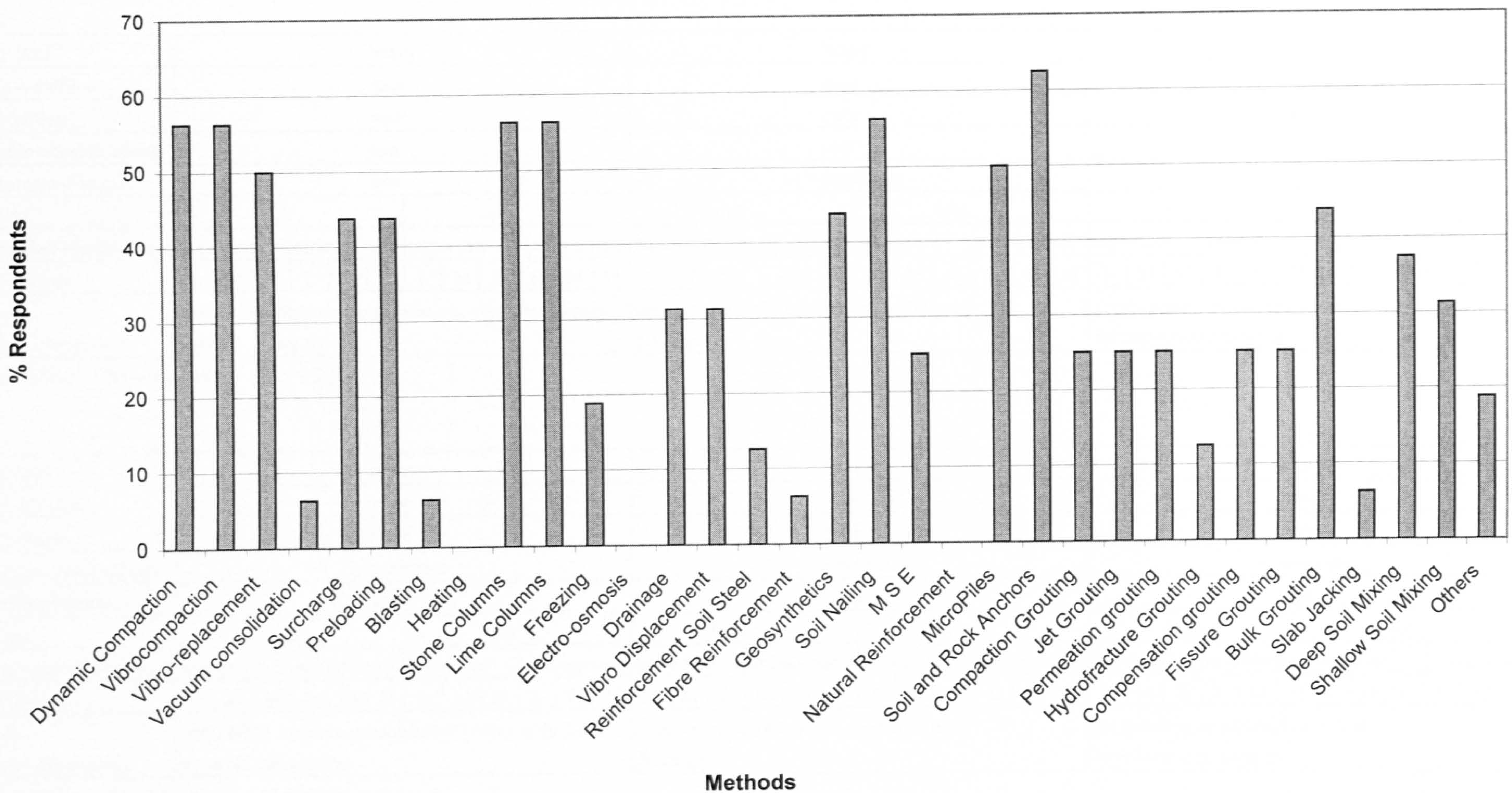
APPENDIX B (continuation)

Parameter Assessment Methods

Factor	Parameter	Assessment	Purpose
Site conditions	boundary conditions		
	a) groundwater levels	borehole measurements CPT if piezocone is used surface water levels	slope stability, bearing capacity, settlement, seepage
	b) soil stratigraphy	SPT samples, CPT interpretation, borehole permeability tests existing boring data	slope stability, bearing capacity, settlement, seepage
	c) high/low permeability layers		slope stability, bearing capacity, settlement, seepage
	d) geometry	from plans of proposed structures, as-built plans or survey for existing structures	slope stability, bearing capacity, settlement
	geologic conditions	geotechnical investigation report	slope stability, bearing capacity, settlement, seepage
	joints or fractures		stability, seepage

APPENDIX C

Preferred Usage of Ground Improvement Methods



APPENDIX D

DECISION TABLES FOR LOAD.

facility load	heavy												heavy												heavy											
ground-condition	poor												poor												poor											
site-condition	poor												poor												poor											
economic-considerations	low												low												low											
environmental-impact	low												moderate												high											
expertise	high						low						high						low						high						low					
construction-related-issues	important			unimportant			important			unimportant			important			unimportant			important			unimportant			important			unimportant			important			unimportant		
miscellaneous	L	M	H	L	M	H	L	M	H	L	M	H	L	M	H	L	M	H	L	M	H	L	M	H	L	M	H	L	M	H	L	M	H	L	M	H
methods (soil type dependent)	preloading, vacuum consolidation, vibro techniques dynamic compaction												lime/cement stabilization, lime columns, drainage												jet grouting, compaction grouting, reinforcement methods											

Notes: L= low   M = Moderate   H = High

facility load	heavy												heavy												heavy											
ground-condition	poor												poor												poor											
site-condition	poor												poor												poor											
economic-considerations	moderate												moderate												moderate											
environmental-impact	low												moderate												high											
expertise	high						low						high						low						high						low					
construction-related-issues	important			unimportant			important			unimportant			important			unimportant			important			unimportant			important			unimportant			important			unimportant		
miscellaneous	L	M	H	L	M	H	L	M	H	L	M	H	L	M	H	L	M	H	L	M	H	L	M	H	L	M	H	L	M	H	L	M	H	L	M	H
methods (soil type dependent)	preloading, vacuum consolidation, vibro techniques dynamic compaction												lime/cement stabilization, lime columns, drainage												jet grouting, compaction grouting reinforcement methods											

Notes: L= low   M = Moderate   H = High

APPENDIX D (continue)

DECISION TABLES FOR LOAD.

facility load	heavy												heavy												heavy											
ground-condition	poor												poor												poor											
site-condition	poor												poor												poor											
economic-considerations	high												high												high											
environmental-impact	low												moderate												high											
expertise	high						low						high						low						high						low					
construction-related-issues	important			unimportant			important			unimportant			important			unimportant			important			unimportant			important			unimportant			important			unimportant		
miscellaneous	L	M	H	L	M	H	L	M	H	L	M	H	L	M	H	L	M	H	L	M	H	L	M	H	L	M	H	L	M	H	L	M	H	L	M	H
methods	low-cost methods eg. preloading, reinforcement,												prefabricated vertical drains, surface compaction												compaction grouting, reinforcement methods											
(soil type dependent)	dynamic compaction																								replacement, stabilization methods											

Notes: L= low M = Moderate H = High

facility load	heavy												heavy												heavy											
ground-condition	poor												poor												poor											
site-condition	good												good												good											
economic-considerations	low												low												low											
environmental-impact	low												moderate												high											
expertise	high						low						high						low						high						low					
construction-related-issues	important			unimportant			important			unimportant			important			unimportant			important			unimportant			important			unimportant			important			unimportant		
miscellaneous	L	M	H	L	M	H	L	M	H	L	M	H	L	M	H	L	M	H	L	M	H	L	M	H	L	M	H	L	M	H	L	M	H	L	M	H
methods	surcharge/preloading, vibrocompaction, drainage												lime/cement stabilization, lime columns, drainage												low environmental impact methods eg, jet grouting,											
(soil type dependent)	dynamic compaction												grouting methods,												compaction grouting, reinforcement methods											

Notes: L= low M = Moderate H = High

APPENDIX D (continue)

DECISION TABLES FOR LOAD.

facility load	heavy											
ground-condition	poor											
site-condition	good											
economic-considerations	moderate											
environmental-impact	low											
expertise	high						low					
construction-related-issues	important			unimportant			important			unimportant		
miscellaneous	L	M	H	L	M	H	L	M	H	L	M	H
methods (soil type dependent)	preloading, vacuum consolidation, vibro techniques dynamic compaction											

facility load	heavy											
ground-condition	poor											
site-condition	good											
economic-considerations	moderate											
environmental-impact	moderate											
expertise	high						low					
construction-related-issues	important			unimportant			important			unimportant		
miscellaneous	L	M	H	L	M	H	L	M	H	L	M	H
methods (soil type dependent)	lime/cement stabilization, lime columns, drainage											

facility load	heavy											
ground-condition	poor											
site-condition	good											
economic-considerations	moderate											
environmental-impact	high											
expertise	high						low					
construction-related-issues	important			unimportant			important			unimportant		
miscellaneous	L	M	H	L	M	H	L	M	H	L	M	H
methods (soil type dependent)	low environmental impact methods eg, jet grouting, compaction grouting, reinforcement methods											

Notes: L= low M = Moderate H = High

facility load	heavy											
ground-condition	poor											
site-condition	good											
economic-considerations	high											
environmental-impact	low											
expertise	high						low					
construction-related-issues	important			unimportant			important			unimportant		
miscellaneous	L	M	H	L	M	H	L	M	H	L	M	H
methods (soil type dependent)	preloading, vacuum consolidation, vibro techniques dynamic compaction, freezing, grouting methods											

facility load	heavy											
ground-condition	poor											
site-condition	good											
economic-considerations	high											
environmental-impact	moderate											
expertise	high						low					
construction-related-issues	important			unimportant			important			unimportant		
miscellaneous	L	M	H	L	M	H	L	M	H	L	M	H
methods (soil type dependent)	lime/cement stabilization, lime columns, drainage, stone surface compaction, blasting											

facility load	heavy											
ground-condition	poor											
site-condition	good											
economic-considerations	high											
environmental-impact	high											
expertise	high						low					
construction-related-issues	important			unimportant			important			unimportant		
miscellaneous	L	M	H	L	M	H	L	M	H	L	M	H
methods (soil type dependent)	ground freezing, jet grouting, vacuum consolidation compaction grouting, reinforcement methods											

Notes: L= low M = Moderate H = High

APPENDIX D (continue)

DECISION TABLES FOR LOAD.

facility load	heavy												heavy												heavy											
ground-condition	good												good												good											
site-condition	poor												poor												poor											
economic-considerations	low												low												low											
environmental-impact	low												moderate												high											
expertise	high						low						high						low						high						low					
construction-related-issues	important			unimportant			important			unimportant			important			unimportant			important			unimportant			important			unimportant			important			unimportant		
miscellaneous	L	M	H	L	M	H	L	M	H	L	M	H	L	M	H	L	M	H	L	M	H	L	M	H	L	M	H	L	M	H	L	M	H	L	M	H
methods	No ground improvement required																																			

Notes: L= low   M = Moderate   H = High

facility load	medium												medium												medium											
ground-condition	poor												poor												poor											
site-condition	poor												poor												poor											
economic-considerations	low												low												low											
environmental-impact	low												moderate												high											
expertise	high						low						high						low						high						low					
construction-related-issues	important			unimportant			important			unimportant			important			unimportant			important			unimportant			important			unimportant			important			unimportant		
miscellaneous	L	M	H	L	M	H	L	M	H	L	M	H	L	M	H	L	M	H	L	M	H	L	M	H	L	M	H	L	M	H	L	M	H	L	M	H
methods (soil type dependent)	grouting techniques, surface compaction, soil nailing fibre reinforcement												lime/cement stabilization, lime columns, drainage stone columns, soil nails, anchors												stabilization, methods, geosynthetics reinforcement											

Notes: L= low   M = Moderate   H = High

APPENDIX D (continue)

DECISION TABLES FOR LOAD.

facility load	medium												medium												medium											
ground-condition	poor												poor												poor											
site-condition	poor												poor												poor											
economic-considerations	moderate												moderate												medium											
environmental-impact	low												moderate												high											
expertise	high						low						high						low						high						low					
construction-related-issues	important			unimportant			important			unimportant			important			unimportant			important			unimportant			important			unimportant			important			unimportant		
miscellaneous	L	M	H	L	M	H	L	M	H	L	M	H	L	M	H	L	M	H	L	M	H	L	M	H	L	M	H	L	M	H	L	M	H	L	M	H
methods (soil type dependent)	preloading, vacuum consolidation, vibro techniques												lime/cement stabilization, lime columns, drainage stone columns, dynamic compaction												low environmental impact methods, freezing compaction grouting, reinforcement methods											

Notes: L= low M = Moderate H = High

facility load	medium												medium												medium											
ground-condition	poor												poor												poor											
site-condition	poor												poor												poor											
economic-considerations	high												high												high											
environmental-impact	low												moderate												high											
expertise	high						low						high						low						high						low					
construction-related-issues	important			unimportant			important			unimportant			important			unimportant			important			unimportant			important			unimportant			important			unimportant		
miscellaneous	L	M	H	L	M	H	L	M	H	L	M	H	L	M	H	L	M	H	L	M	H	L	M	H	L	M	H	L	M	H	L	M	H	L	M	H
methods (soil type dependent)	preloading, vacuum consolidation, vibro techniques stabilization techniques												lime/cement stabilization, lime columns, drainage surface compaction, penetration grouting												low environmental impact methods eg, jet grouting, compaction grouting, reinforcement methods											

Notes: L= low M = Moderate H = High

APPENDIX D (continue)

DECISION TABLES FOR LOAD.

<table>
<tr><td>facility load</td><td colspan="12">medium</td><td colspan="12">medium</td><td colspan="12">medium</td></tr>
<tr><td>ground-condition</td><td colspan="12">poor</td><td colspan="12">poor</td><td colspan="12">poor</td></tr>
<tr><td>site-condition</td><td colspan="12">good</td><td colspan="12">good</td><td colspan="12">good</td></tr>
<tr><td>economic-considerations</td><td colspan="12">low</td><td colspan="12">low</td><td colspan="12">low</td></tr>
<tr><td>environmental-impact</td><td colspan="12">low</td><td colspan="12">moderate</td><td colspan="12">high</td></tr>
<tr><td>expertise</td><td colspan="6">high</td><td colspan="6">low</td><td colspan="6">high</td><td colspan="6">low</td><td colspan="6">high</td><td colspan="6">low</td></tr>
<tr><td>construction-related-issues</td><td colspan="3">important</td><td colspan="3">unimportant</td><td colspan="3">important</td><td colspan="3">unimportant</td><td colspan="3">important</td><td colspan="3">unimportant</td><td colspan="3">important</td><td colspan="3">unimportant</td><td colspan="3">important</td><td colspan="3">unimportant</td><td colspan="3">important</td><td colspan="3">unimportant</td></tr>
<tr><td>miscellaneous</td><td>L</td><td>M</td><td>H</td><td>L</td><td>M</td><td>H</td><td>L</td><td>M</td><td>H</td><td>L</td><td>M</td><td>H</td><td>L</td><td>M</td><td>H</td><td>L</td><td>M</td><td>H</td><td>L</td><td>M</td><td>H</td><td>L</td><td>M</td><td>H</td><td>L</td><td>M</td><td>H</td><td>L</td><td>M</td><td>H</td><td>L</td><td>M</td><td>H</td><td>L</td><td>M</td><td>H</td></tr>
<tr><td>methods
(soil type dependent)</td><td colspan="12">preloading, vacuum consolidation, vibro techniques
dynamic compaction</td><td colspan="12">lime/cement stabilization, lime columns, drainage</td><td colspan="12">low environmental impact methods eg, jet grouting,
compaction grouting, reinforcement methods</td></tr>
</table>

Notes: L= low   M = Moderate   H = High

<table>
<tr><td>facility load</td><td colspan="12">medium</td><td colspan="12">medium</td><td colspan="12">medium</td></tr>
<tr><td>ground-condition</td><td colspan="12">poor</td><td colspan="12">poor</td><td colspan="12">poor</td></tr>
<tr><td>site-condition</td><td colspan="12">good</td><td colspan="12">good</td><td colspan="12">good</td></tr>
<tr><td>economic-considerations</td><td colspan="12">moderate</td><td colspan="12">moderate</td><td colspan="12">moderate</td></tr>
<tr><td>environmental-impact</td><td colspan="12">low</td><td colspan="12">moderate</td><td colspan="12">high</td></tr>
<tr><td>expertise</td><td colspan="6">high</td><td colspan="6">low</td><td colspan="6">high</td><td colspan="6">low</td><td colspan="6">high</td><td colspan="6">low</td></tr>
<tr><td>construction-related-issues</td><td colspan="3">important</td><td colspan="3">unimportant</td><td colspan="3">important</td><td colspan="3">unimportant</td><td colspan="3">important</td><td colspan="3">unimportant</td><td colspan="3">important</td><td colspan="3">unimportant</td><td colspan="3">important</td><td colspan="3">unimportant</td><td colspan="3">important</td><td colspan="3">unimportant</td></tr>
<tr><td>miscellaneous</td><td>L</td><td>M</td><td>H</td><td>L</td><td>M</td><td>H</td><td>L</td><td>M</td><td>H</td><td>L</td><td>M</td><td>H</td><td>L</td><td>M</td><td>H</td><td>L</td><td>M</td><td>H</td><td>L</td><td>M</td><td>H</td><td>L</td><td>M</td><td>H</td><td>L</td><td>M</td><td>H</td><td>L</td><td>M</td><td>H</td><td>L</td><td>M</td><td>H</td><td>L</td><td>M</td><td>H</td></tr>
<tr><td>methods
(soil type dependent)</td><td colspan="12">preloading, vacuum consolidation, vibro techniques
dynamic compaction, grouting techniques</td><td colspan="12">All methods applicable depending on soil type</td><td colspan="12">drainage, grouting methods, geosynthetics</td></tr>
</table>

Notes: L= low   M = Moderate   H = High

APPENDIX D (continue)

DECISION TABLES FOR LOAD.

facility load	medium												medium												medium											
ground-condition	poor												poor												poor											
site-condition	good												good												good											
economic-considerations	high												high												high											
environmental-impact	low												moderate												high											
expertise	high						low						high						low						high						low					
construction-related-issues	important			unimportant			important			unimportant			important			unimportant			important			unimportant			important			unimportant			important			unimportant		
miscellaneous	L	M	H	L	M	H	L	M	H	L	M	H	L	M	H	L	M	H	L	M	H	L	M	H	L	M	H	L	M	H	L	M	H	L	M	H
methods (soil type dependent)	most methods except expensive ones such as ground freezir deep mixing technique, dynamic compaction, blast																								vibro techniques such as vibro replacement,											

Notes: L= low M = Moderate H = High

facility load	medium												medium												medium											
ground-condition	good												good												good											
site-condition	good												good												good											
economic-considerations	high												high												high											
environmental-impact	low												moderate												high											
expertise	high						low						high						low						high						low					
construction-related-issues	important			unimportant			important			unimportant			important			unimportant			important			unimportant			important			unimportant			important			unimportant		
miscellaneous	L	M	H	L	M	H	L	M	H	L	M	H	L	M	H	L	M	H	L	M	H	L	M	H	L	M	H	L	M	H	L	M	H	L	M	H
methods (soil type dependent)	ground improvement not necessary																																			

Notes: L= low M = Moderate H = High

APPENDIX D (continue)

DECISION TABLES FOR LOAD.

<table>
<tr><td>facility load</td><td colspan="12">light</td><td colspan="12">light</td><td colspan="12">light</td></tr>
<tr><td>ground-condition</td><td colspan="12">poor</td><td colspan="12">poor</td><td colspan="12">poor</td></tr>
<tr><td>site-condition</td><td colspan="12">poor</td><td colspan="12">poor</td><td colspan="12">poor</td></tr>
<tr><td>economic-considerations</td><td colspan="12">low</td><td colspan="12">low</td><td colspan="12">low</td></tr>
<tr><td>environmental-impact</td><td colspan="12">low</td><td colspan="12">moderate</td><td colspan="12">high</td></tr>
<tr><td>expertise</td><td colspan="6">high</td><td colspan="6">low</td><td colspan="6">high</td><td colspan="6">low</td><td colspan="6">high</td><td colspan="6">low</td></tr>
<tr><td>construction-related-issues</td><td colspan="3">important</td><td colspan="3">unimportant</td><td colspan="3">important</td><td colspan="3">unimportant</td><td colspan="3">important</td><td colspan="3">unimportant</td><td colspan="3">important</td><td colspan="3">unimportant</td><td colspan="3">important</td><td colspan="3">unimportant</td><td colspan="3">important</td><td colspan="3">unimportant</td></tr>
<tr><td>miscellaneous</td><td>L</td><td>M</td><td>H</td><td>L</td><td>M</td><td>H</td><td>L</td><td>M</td><td>H</td><td>L</td><td>M</td><td>H</td><td>L</td><td>M</td><td>H</td><td>L</td><td>M</td><td>H</td><td>L</td><td>M</td><td>H</td><td>L</td><td>M</td><td>H</td><td>L</td><td>M</td><td>H</td><td>L</td><td>M</td><td>H</td><td>L</td><td>M</td><td>H</td><td>L</td><td>M</td><td>H</td></tr>
<tr><td>methods
(soil type dependent)</td><td colspan="12">surcharge loading, weight reduction, surface
compaction, soil nails, stabilization techniques</td><td colspan="12">lime/cement stabilization, lime columns, drainage
stone columns, dynamic compaction</td><td colspan="12">grouting methods, reinforcement methods,blasting
light weight fill</td></tr>
</table>

Notes: L= low M = Moderate H = High

<table>
<tr><td>facility load</td><td colspan="12">light</td><td colspan="12">light</td><td colspan="12">light</td></tr>
<tr><td>ground-condition</td><td colspan="12">poor</td><td colspan="12">poor</td><td colspan="12">poor</td></tr>
<tr><td>site-condition</td><td colspan="12">poor</td><td colspan="12">poor</td><td colspan="12">poor</td></tr>
<tr><td>economic-considerations</td><td colspan="12">moderate</td><td colspan="12">moderate</td><td colspan="12">medium</td></tr>
<tr><td>environmental-impact</td><td colspan="12">low</td><td colspan="12">moderate</td><td colspan="12">high</td></tr>
<tr><td>expertise</td><td colspan="6">high</td><td colspan="6">low</td><td colspan="6">high</td><td colspan="6">low</td><td colspan="6">high</td><td colspan="6">low</td></tr>
<tr><td>construction-related-issues</td><td colspan="3">important</td><td colspan="3">unimportant</td><td colspan="3">important</td><td colspan="3">unimportant</td><td colspan="3">important</td><td colspan="3">unimportant</td><td colspan="3">important</td><td colspan="3">unimportant</td><td colspan="3">important</td><td colspan="3">unimportant</td><td colspan="3">important</td><td colspan="3">unimportant</td></tr>
<tr><td>miscellaneous</td><td>L</td><td>M</td><td>H</td><td>L</td><td>M</td><td>H</td><td>L</td><td>M</td><td>H</td><td>L</td><td>M</td><td>H</td><td>L</td><td>M</td><td>H</td><td>L</td><td>M</td><td>H</td><td>L</td><td>M</td><td>H</td><td>L</td><td>M</td><td>H</td><td>L</td><td>M</td><td>H</td><td>L</td><td>M</td><td>H</td><td>L</td><td>M</td><td>H</td><td>L</td><td>M</td><td>H</td></tr>
<tr><td>methods
(soil type dependent)</td><td colspan="12">preloading, vacuum consolidation, vibro techniques
dynamic compaction</td><td colspan="12">lime/cement stabilization, lime columns, drainage</td><td colspan="12">light weight fill, vacuum consolidationslurry walls</td></tr>
</table>

Notes: L= low M = Moderate H = High

APPENDIX D (continue)

DECISION TABLES FOR LOAD.

facility load	light												light												light											
ground-condition	poor												poor												poor											
site-condition	poor												poor												poor											
economic-considerations	high												high												high											
environmental-impact	low												moderate												high											
expertise	high						low						high						low						high						low					
construction-related-issues	important			unimportant			important			unimportant			important			unimportant			important			unimportant			important			unimportant			important			unimportant		
miscellaneous	L	M	H	L	M	H	L	M	H	L	M	H	L	M	H	L	M	H	L	M	H	L	M	H	L	M	H	L	M	H	L	M	H	L	M	H
methods (soil type dependent)	grouting techniques, soil nailing, geosynthetics, reinforcement												lime/cement stabilization, lime columns, drainage												lightweight fill, geosynthetics, reinforcement,											

Notes: L= low M = Moderate H = High

facility load	light												light												light											
ground-condition	poor												poor												poor											
site-condition	good												good												good											
economic-considerations	low												low												low											
environmental-impact	low												moderate												high											
expertise	high						low						high						low						high						low					
construction-related-issues	important			unimportant			important			unimportant			important			unimportant			important			unimportant			important			unimportant			important			unimportant		
miscellaneous	L	M	H	L	M	H	L	M	H	L	M	H	L	M	H	L	M	H	L	M	H	L	M	H	L	M	H	L	M	H	L	M	H	L	M	H
methods (soil type dependent)	preloading, vacuum consolidation, vibro techniques dynamic compaction												lime/cement stabilization, lime columns, drainage preloading, vibro techniques												permeation grouting, vibro replacement, surface compaction, reinforcement methods											

Notes: L= low M = Moderate H = High

APPENDIX D (continue)

DECISION TABLES FOR LOAD.

facility load	light												light												light											
ground-condition	poor												poor												poor											
site-condition	good												good												good											
economic-considerations	moderate												moderate												moderate											
environmental-impact	low												moderate												high											
expertise	high						low						high						low						high						low					
construction-related-issues	important			unimportant			important			unimportant			important			unimportant			important			unimportant			important			unimportant			important			unimportant		
miscellaneous	L	M	H	L	M	H	L	M	H	L	M	H	L	M	H	L	M	H	L	M	H	L	M	H	L	M	H	L	M	H	L	M	H	L	M	H
methods (soil type dependent)	all methods depending on soil type and application																								most methods											

Notes: L= low M = Moderate H = High

facility load	light												light												light											
ground-condition	poor												poor												poor											
site-condition	good												good												good											
economic-considerations	high												high												high											
environmental-impact	low												moderate												high											
expertise	high						low						high						low						high						low					
construction-related-issues	important			unimportant			important			unimportant			important			unimportant			important			unimportant			important			unimportant			important			unimportant		
miscellaneous	L	M	H	L	M	H	L	M	H	L	M	H	L	M	H	L	M	H	L	M	H	L	M	H	L	M	H	L	M	H	L	M	H	L	M	H
methods (soil type dependent)	low cost methods such as preloading, surface compaction,												dynamic compaction, vibro methods, stabilization techniques												low cost methods such as preloading, biotechnical stabilization, compaction grouting, reinforcement											

Notes: L= low M = Moderate H = High

APPENDIX D (continue)

DECISION TABLES FOR LOAD.

<table>
<tr><td>facility load</td><td colspan="12">light</td><td colspan="12">light</td><td colspan="12">light</td></tr>
<tr><td>ground-condition</td><td colspan="12">good</td><td colspan="12">good</td><td colspan="12">good</td></tr>
<tr><td>site-condition</td><td colspan="12">good</td><td colspan="12">good</td><td colspan="12">good</td></tr>
<tr><td>economic-considerations</td><td colspan="12">high</td><td colspan="12">high</td><td colspan="12">high</td></tr>
<tr><td>environmental-impact</td><td colspan="12">low</td><td colspan="12">moderate</td><td colspan="12">high</td></tr>
<tr><td>expertise</td><td colspan="6">high</td><td colspan="6">low</td><td colspan="6">high</td><td colspan="6">low</td><td colspan="6">high</td><td colspan="6">low</td></tr>
<tr><td>construction-related-issues</td><td colspan="3">important</td><td colspan="3">unimportant</td><td colspan="3">important</td><td colspan="3">unimportant</td><td colspan="3">important</td><td colspan="3">unimportant</td><td colspan="3">important</td><td colspan="3">unimportant</td><td colspan="3">important</td><td colspan="3">unimportant</td><td colspan="3">important</td><td colspan="3">unimportant</td></tr>
<tr><td>miscellaneous</td><td>L</td><td>M</td><td>H</td><td>L</td><td>M</td><td>H</td><td>L</td><td>M</td><td>H</td><td>L</td><td>M</td><td>H</td><td>L</td><td>M</td><td>H</td><td>L</td><td>M</td><td>H</td><td>L</td><td>M</td><td>H</td><td>L</td><td>M</td><td>H</td><td>L</td><td>M</td><td>H</td><td>L</td><td>M</td><td>H</td><td>L</td><td>M</td><td>H</td><td>L</td><td>M</td><td>H</td></tr>
<tr><td>methods
(soil type dependent)</td><td colspan="36">ground improvement not necessary</td></tr>
</table>

Notes: L= low M = Moderate H = High

APPENDIX E

PROBLEMATIC SOIL IDENTIFICATION PARAMETERS

Soft clay

property	value/description
major division	Fine grained
grain size (mm)	<0.002
clay fraction (%)	>50
clay mineralogy	Illite, kaolinite, montmorillonite, chlorite
w_L (%)	<50
I_p (%)	>7 $4 \leq I_p \leq 7$ <4
q_u (kPa)	<50
S_u (kPa)	<25
void ratio, e	High
C_c	>0.3
k(m/s)	10^{-8}-10^{-5}
S_t	>10
relative density	15-35
SPT N-value	<4

Expansive Clay

property	value/description
major division	Fine grained
grain size (mm)	<0.002
clay fraction (%)	>50
clay mineralogy	Illite, chlorite montmorillonite,
w_L (%)	>50
I_p (%)	>12
shrinkage limit (%)	<12
activity	<1.25
expansion index	>50
(EI)	>0.5
swell potential	>50
expansive soil indices (ESI)	>1.15
k(m/s)	10^{-8}-10^{-5}

Collapsible soil

property	value/description
major division	Fine-coarse grained
grain size (mm)	<0.06
w_L (%)	<45
I_p (%)	<25
void ratio, e	>0.8
porosity, n, (%)	40-60
dry density (t/m^3)	1.01- 1.65
collapse potential	>1

Organic soils: peat

property	value/description
major division	Highly organic
grain size (mm)	
(peat)	Sand- silt range
(organic soils)	Silt-clay range
moisture content (%)	Very high
void ratio, e	>9
shrinkage (%)	10-75
dry density (t/m^3)	0.65- 1.20
compressibility, m_v, (m^2/MN)	>1.5
organic content (%)	>3
ash content (%)	
(peat and peaty soil)	<40
(organic soils)	>40
fibre content (%)	
(peat)	>50
(peaty soil)	<50

Liquefiable soil

property	value/description
major division	Fine-coarse grained
grain size (mm)	0.6-0.02
w_L (%)	<45
I_p (%)	<25
void ratio, e	>0.8
porosity, n, (%)	40-60
dry density (t/m^3)	1.01- 1.65

APPENDIX F.1

Densification Techniques

Condition	subcondition	Improvement methods				
		dynamic compaction	vibro-compaction	compaction grouting	blasting	surface compaction
type-improvement		permanent	permanent	permanent	permanent	permanent
		temporary	temporary	temporary	temporary	temporary
depth-application		deep	deep	deep	deep	shallow
			shallow	shallow		
application (control following)		bc	bc	bc	bc	bc
		settlement		settlement	settlement	settlement
		environmental				environmental
		liquefaction	liquefaction		liquefaction	
ground-condition	soil-type	loose-granular	loose-granular	loose-granular	loose-granular	cohesive
		weak-granular	weak-granular	soft-soil	weak-granular	granular
		soft-soil	clean sands	non-saturated		
		uncontrolled fill	(<12-15% silt)	fine-soil	hydraulic fill	fill
		collapsible soil	fill	collapsible soil		
		clayey-soil (Ip>8)				
	thickness	medium	medium	medium	medium	thin
		thick (max 8m)	thick	thick	thick	medium
				thin		
	stratigraphy	simple	simple	simple	simple	simple
		complex	complex	complex	complex	
	water table	WT-high	WT-high	WT-high	WT-high	
		WT-moderate		WT-moderate	WT-moderate	
		WT-low	WT-low	WT-low	WT-low	WT-low
	permeability	semi-pervious	semi-pervious	semi-pervious	semi-prvious	pervious
		pervious	pervious	pervious	pervious	impervious
		impervious				
	saturation	partial	partial	partial	saturated	
		saturated	saturated	saturated		saturated

Note: bc= bearing capacity increase

APPENDIX F.1 (CONTINUE)

Densification Techniques

Condition	subcondition	Improvement methods				
		dynamic compaction	vibro-compaction	compaction grouting	blasting	surface compaction
site-condition	project-site-area		large	small	large	large small
	site-confinement	open	open	open confined	open confined	open
	site-accessibility	accessible	accessible	inaccessible	accessible inaccessible	accessible
	site-topography	even	even	even, uneven	even, uneven	even, uneven
	site-stability	stable	stable		stable	stable
	headroom	yes	yes	no	no	no
	surface-restraints	no	no	yes	yes	yes
	subsurface-restraints	no	no	yes	yes	no
	development	undeveloped	undeveloped	developed	undeveloped	undeveloped
construction-related-issues	time-requirement	immediate long-term	immediate long-term	immediate	immediate long-term	immediate
	maintenance	yes	yes	no	no	yes
	material-durability	low	low	yes	no	no
	material-availability	no	yes	yes	no	yes
	expertise-requirement	high	high	high	low	low
	labour-requirement	skilled semi-skilled	skilled semi-skilled	skilled	unskilled	skilled semi-skilled
	equipment-availability	yes	yes	yes	yes	yes
economic-considerations	relative-cost	low	moderate	high	low	low
	contractor-availability	local	local	no	no	no
environmental-impact	noise	high	low	low	low	low
	vibrations	high	high	low	yes	low
	groundwater-pollution	high	high	low	no	no
	surface-water-pollution	high	high	low	no	no
tradition		yes	yes	no	no	no
geographic-limits		no	no	no	no	no

Note: bc = bearing capacity increase

APPENDIX F.2

Consolidation Techniques

Condition	subcondition	Improvement methods				
		preloading	vacuum-consolidation	electro-osmosis	PV-drains	stone columns
type-improvement		permanent	permanent	permanent	permanent	permanent
depth-application		deep	deep	deep	deep	deep
			shallow	shallow		
application (control following)		bc	bc	bc	bc	bc
		settlement	settlement	settlement	settlement	settlement
		liquefaction			liquefaction	environmental
						liquefaction
						stability
ground-condition	soil-type	soft-cohesive	soft-cohesive	soft-cohesive	soft-cohesive	soft-cohesive
		organic-silt		compressible	compressible	loose-sands
		dredged materials		sands		peat
	thickness	medium	medium	medium	medium	thick
		thin	thick	thick	thick	medium
				thin		
	stratigraphy	simple	simple	simple	simple	simple
			complex	complex	complex	complex
	water table	WT-high	WT-high	WT-high	WT-high	
		WT-moderate	WT-moderate	WT-moderate	WT-moderate	
		WT-low		WT-low	WT-low	WT-low
	permeability	semi-pervious	impervious	semi-pervious	semi-prvious	pervious
		pervious		impervious	impervious	impervious
	saturation	saturated	saturated	partial	saturated	saturated
				saturated		

Note: bc = bearing capacity increase

APPENDIX F.2 (Continue)

Consolidation Techniques

Condition	Subcondition	Improvement methods				
		preloading	vacuum-consolidation	electro-osmosis	PV-drains	stone columns
site-condition	project-site-area	large small	large	small	large small	large, small
	site-confinement	open	open	open confined	open	open
	site-accessibility	accessible	accessible	inaccessible	accessible inaccessible	accessible
	site-topography	even	even	even, uneven	even	even, uneven
	site-stability	stable	stable	stable	stable	stable
	headroom	no	yes	no	yes	yes
	surface-restraints	no	no	no	no	no
	development	undeveloped	undeveloped	developed	undeveloped	undeveloped
	subsurface-restraints	no	no	no	no	no
construction-related-issues	time-requirement	long-term	immediate long-term	immediate	immediate continous	immediate long-term
	maintenance	no	yes	no	yes	yes
	material-durability	low	high	no	yes	yes
	material-availability	yes	yes	no	yes	yes
	expertise-requirement	low	high	high	high	high
	labour-requirement	unskilled semi-skilled	skilled semi-skilled	skilled	skilled	skilled semi-skilled
	equipment-availability	no	yes	yes	yes	yes
economic-considerations	relative-cost	low	moderate	high	moderate	moderate
	contractor-availability	local	local	yes	yes	no
environmental-impact	noise	low	low	low	low	low
	vibrations	low	low	low	high	low
	groundwater-pollution	high	high	low	low	high
	surface-water-pollution	high	high	high	high	low
tradition		no	yes	no	no	no
geographic-limits		no	no	no	no	no

Note: bc = bearing capacity increase

APPENDIX F.3

Reinforcement Techniques

Condition	subcondition	Improvement methods				
		mechanical-satbilization	soil nailing	soil & rock anchoring	micropiles	fiber reinforcement
type-improvement		permanent	temporary	permanent	permanent	permanent
				temporary	remedial	
depth-application		deep	deep	deep	deep	shallow
		shallow	shallow	shallow		
application (control following)		bc	stability	stability	stability	bc
		settlement	resistance to		settlement	settlement
		stability	deformation		underpinning	environmental
					seismic retro-	liquefaction
					fit	stability
ground-condition	soil-type	granular with	clays,sandy-	cohesive	all types,	granular
		<15%fines	soils, stratified	cohesionless	artificial	compressible
		all types	soils			cohesive
	thickness	medium	medium	medium	medium	thick
		thin	thick	thick	thick	medium
		thick		thin		
	stratigraphy	simple	simple	simple	simple	simple
		complex	complex	complex	complex	complex
	water table	WT-high	WT-high	WT-high	WT-high	
		WT-moderate	WT-moderate	WT-moderate	WT-moderate	
		WT-low	WT-low	WT-low	WT-low	
	permeability	semi-pervious	semi-pervious	semi-pervious	semi-prvious	semi-prvious
		pervious	pervious	impervious	impervious	pervious
			impervious		pervious	impervious
	saturation	dry	dry	dry	dry	dry
		partial	saturated	partial	partial	partial
		saturated	partial	saturated	saturated	saturated

Note: bc = bearing capacity increase

APPENDIX F.3 (Continue)

Reinforcement Techniques

Condition	Subcondition	Improvement methods				
		mechanical-satbilization	soil nailing	soil & rock anchoring	micropiles	fiber reinforcement
site-condition	project-site-area	large small	small	large sma;ll	small	large small
	site-confinement	open confined	open	open confined	open confined	open confined
	site-accessibility	accessible inaccessible	accessible	inaccessible	accessible inaccessible	accessible
	site-topography	even, uneven	even,uneven	even, uneven	even, uneven	even, uneven
	site-stability	stable	stable	stable	stable	stable
	headroom	no	yes	yes	yes	no
	surface-restraints	no	yes	no	yes	no
	development	developed	developed	developed	developed	developed
	subsurface-restraints	no	yes	no	no	no
construction-related-issues	time-requirement	long-term immediate	immediate long-term	immediate long-term	immediate long-term	immediate long-term
	maintenance	no	yes	no	yes	no
	material-durability	high	high	no	yes	yes
	material-availability	yes	yes	no	yes	yes
	expertise-requirement	high	high	high	high	high
	labour-requirement	unskilled semi-skilled	skilled semi-skilled	skilled	skilled	skilled semi-skilled
	equipment-availability	no	yes	yes	yes	yes
economic-considerations	relative-cost	moderate	moderate	high	high	moderate
	contractor-availability	no	no	yes	yes	yes
environmental-impact	noise	low	low	low	low	low
	vibrations	low	low	low	low	low
	groundwater-pollution	low	low	low	low	low
	surface-water-pollution	low	low	high	high	low
tradition		no	yes	no	yes	no
geographic-limits		no	no	no	no	no

Note: bc = bearing capacity increase

APPENDIX F.4

Chemical Treatment Methods: Grouting Techniques

Condition	subcondition	Improvement methods			
		jet grouting	permeation grouting	fracture grouting	slurry grouting
type-improvement		permanent	permanent	permanent	permanent
					remedial
depth-application		deep	deep	deep	deep
			shallow	shallow	
application (control following)		bc	stability	stability	stability
		settlement	resistance to deformation	settlement	settlement
		stability			underpinning
		groundwater	groundwater		seismic retro-fit
		evnvironmental			
		liquefaction			
ground-condition	soil-type	all types	sands	cohesive	gravels
				all soil types	rocks
	thickness	medium	medium	medium	medium
		thin	thick	thick	thick
		thick		thin	
	stratigraphy	simple	simple	simple	simple
		complex	complex	complex	complex
	water table	WT-high	WT-high	WT-high	
		WT-moderate	WT-low	WT-moderate	
		WT-low		WT-low	WT-low
	permeability	semi-pervious	pervious	semi-pervious	semi-prvious
		impervious		impervious	impervious
	saturation	partial	partial	partial	unsaturated
		saturated		saturated	saturated

Note: bc = bearing capacity increase

APPENDIX F.4 (Continue)

Chemical Treatment Methods: Grouting Techniques

Condition	subcondition	Improvement methods			
		jet grouting	permeation grouting	fracture grouting	slurry grouting
site-condition	project-site-area	small	small	small	large small
	site-confinement	open confined	open confined	open confined	open confined
	site-accessibility	accessible inaccessible	accessible inaccessible	inaccessible accessible	accessible inaccessible
	site-topography				
	site-stability	stable	stable	stable	stable
	headroom	no	yes	no	yes
	surface-restraints	no	yes	no	yes
	development	developed	developed	developed	developed
	subsurface-restraints	no	yes	no	no
construction-related-issues	time-requirement	immediate	immediate long-term	immediate	immediate
	maintenance	yes	yes	no	yes
	material-durability	high	high	no	yes
	material-availability	yes	yes	yes	yes
	expertise-requirement	high	high	high	high
	labour-requirement	skilled	skilled	skilled	skilled
	equipment-availability	yes	yes	yes	yes
economic-considerations	relative-cost	high	moderate	high	high
	contractor-availability	no	local	yes	yes
environmental-impact	noise	low	low	low	low
	vibrations	low	low	low	low
	groundwater-pollution	low	low	low	low
	surface-water-pollution	high	high	high	high
tradition		yes	yes	no	no
geographic-limits		no	yes	no	no

Note: bc = bearing capacity increase

APPENDIX F.5

Chemical Treatment Methods: (Mix-in-place Techniques)

Condition	subcondition	Improvement methods			
		shallow soil mix	deep soil mix lime/cement columns	deep soil mix (slurry)	slurry wall
type-improvement		permanent	permanent	permanent	permanent
depth-application		shallow	deep	deep	deep
					shallow
application (control following)		bc	stability	stability	
		settlement	resistance to		groundwater
		stability	deformation		containment
			groundwater		
		evnvironmental	liquefaction		
ground-condition	soil-type	all types	most soil types	soft-cohesive	all types
				compressible	artificial
	thickness	medium	medium	medium	medium
		thin	thick	thick	thick
		thick			
	stratigraphy	simple	simple	simple	simple
		complex	complex	complex	complex
	water table	WT-low	WT-high	WT-high	WT-high
			WT-moderate	WT-moderate	WT-moderate
			WT-low	WT-low	WT-low
	permeability	semi-pervious	semi-pervious	semi-pervious	semi-prvious
		pervious	pervious	impervious	pervious
		impervious	impervious		
	saturation	partial	partial	partial	partial
				saturated	saturated

Note: bc = bearing capacity increase

APPENDIX F.5

Chemical Treatment Methods: (Mix-in-place Techniques)

Condition	subcondition	Improvement methods			
		shallow soil mix	deep soil mix lime/cement columns	deep soil mix (slurry)	slurry wall
type-improvement		permanent	permanent	permanent	permanent
depth-application		shallow	deep	deep	deep
					shallow
application (control following)		bc	stability	stability	
		settlement	resistance to		groundwater
		stability	deformation		containment
			groundwater		
		evnvironmental	liquefaction		
ground-condition	soil-type	all types	most soil types	soft-cohesive	all types
				compressible	artificial
	thickness	medium	medium	medium	medium
		thin	thick	thick	thick
		thick			
	stratigraphy	simple	simple	simple	simple
		complex	complex	complex	complex
	water table	WT-low	WT-high	WT-high	WT-high
			WT-moderate	WT-moderate	WT-moderate
			WT-low	WT-low	WT-low
	permeability	semi-pervious	semi-pervious	semi-pervious	semi-prvious
		pervious	pervious	impervious	pervious
		impervious	impervious		
	saturation	partial	partial	partial	partial
				saturated	saturated

Note: bc = bearing capacity increase

APPENDIX F.5 (continue)

Chemical Treatment Methods: (Mix-in-place Techniques)

Condition	subcondition	Improvement methods			
		shallow soil mix	deep soil mix lime/cement columns	deep soil mix (slurry)	slurry wall
site-condition	project-site-area	small	large	large	large
	site-confinement	open confined	open	open	open
	site-accessibility	accessible inaccessible	accessible	accessible	accessible
	site-topography	even, uneven	even,uneven	even, uneven	even, uneven
	site-stability	stable	stable	stable	stable
	headroom	no	yes	yes	yes
	surface-restraints	no	yes	no	no
	development	undeveloped	undeveloped	developed	undeveloped
	subsurface-restraints	no	no	no	no
construction-related-issues	time-requirement	immediate long-term	immediate long-term	immediate long-term	immediate long-term
	maintenance	no	yes	no	yes
	material-durability	high	high	no	yes
	material-availability	yes	yes	no	yes
	expertise-requirement	high	high	high	high
	labour-requirement	skilled semi-skilled	skilled semi-skilled	skilled	skilled
	equipment-availability	yes	yes	yes	yes
economic-considerations	relative-cost	moderate	high	high	high
	contractor-availability	no	local	yes	yes
environmental-impact	noise	low	low	low	low
	vibrations	low	low	low	low
	groundwater-pollution	low	high	low	low
	surface-water-pollution	low	high	high	low
tradition		no	yes	no	no
geographic-limits		no	yes	no	no
Note: bc = bearing capacity increase					

APPENDIX F.6

Electrotreatment

Condition	subcondition	Improvement methods			
		electrokinetic remediation	electroheating	electrokinetic fencing	bioelectrokinetic injection
type-improvement		permanent	permanent	permanent	permanent
					remedial
depth-application		deep	deep	deep	deep
		shallow	shallow	shallow	
application (control following)		remediation of	remediation of	remediation of	remediation of
		contaminated	contaminated	contaminated	contaminated
		land	land	land	land
		evnvironmental			
ground-condition	soil-type	all types	all types	all types	all types,
		soft clays			artificial
	thickness	medium	medium	medium	medium
		thick	thick	thick	thick
				thin	
	stratigraphy	simple	simple	simple	simple
		complex	complex	complex	complex
	water table	WT-high		WT-high	WT-low
		WT-moderate		WT-moderate	
	permeability	semi-pervious	semi-pervious	semi-pervious	semi-prvious
		impervious	impervious	impervious	impervious
					pervious
	saturation	saturated	partial	partial	unsaturated
				saturated	saturated

Note: bc = bearing capacity increase

APPENDIX F.6 (Continue)

Electrotreatment

Condition	subcondition	Improvement methods			
		electrokinetic remediation	electroheating	electrokinetic fencing	bioelectrokinetic injection
site-condition	project-site-area	small	large	small	large small
	site-confinement	open confined	open	open confined	open confined
	site-accessibility	accessible inaccessible	accessible	inaccessible accessible	accessible inaccessible
	site-topography	even, uneven	even,uneven	even, uneven	even, uneven
	site-stability	stable	stable	stable	stable
	headroom	no	no	no	yes
	surface-restraints	yes	yes	yes	yes
	subsurface-restraints	no	no	no	no
construction-related-issues	time-requirement	long-term immediate	immediate long-term	immediate	immediate
	maintenance	yes	yes	yes	yes
	material-durability	high	high	high	yes
	material-availability	no	no	no	yes
	expertise-requirement	high	high	high	high
	labour-requirement	skilled	skilled semi-skilled	skilled	skilled
	equipment-availability	no	yes	yes	yes
economic-considerations	relative-cost	high	moderate	high	high
	contractor-availability	no	local	yes	yes
environmental-impact	noise	low	low	low	low
	vibrations	low	low	low	low
	groundwater-pollution	low	high	low	low
	surface-water-pollution	low	high	high	low
tradition		no	yes	no	no
geographic-limits		no	yes	no	no

Note: bc = bearing capacity increase

APPENDIX F.7

Weight Reduction, Thermal Stabilization and Biotechnical Stabilization

Condition	subcondition	weight reduction	thermal stabilization		biotechnical stabilization
			ground freezing	vitrification	
type-improvement		permanent	temporary	permanent	permanent
		temporary			temporary
depth-application		shallow	deep	deep	shallow
		deep	shallow		
application (control following)		bc	stability		stability
		settlement	seepage control	environmental	
		stability	environmental		
		earthquake resist-ance			
ground-condition	soil-type	soft compressible	most soil types	contaminated	all types
					artificial
	thickness	medium	medium	medium	medium
		thin	thick	thick	thick
					thin
	stratigraphy	simple	simple	simple	simple
		complex	complex	complex	complex
	water table	WT-high	WT-high	WT-high	
			WT-moderate	WT-moderate	WT-moderate
			WT-low	WT-low	WT-low
	permeability	semi-pervious	semi-pervious	semi-pervious	semi-prvious
		impervious	impervious	impervious	pervious
				pervious	
	saturation	partial	partial		partial
		saturated	saturated		saturated

Note: bc = bearing capacity increase

APPENDIX F.7 (continue)

Weight Reduction, Thermal Stabilization and Biotechnical Stabilization

Condition	subcondition	weight reduction	thermal stabilization		biotechnical stabilization
			ground freezing	vitrification	
site-condition	project-site-area	small	large small	small	large small
	site-confinement	open confined	confined	confined	open confined
	site-accessibility	accessible	accessible inaccessible	accessible inaccessible	accessible inaccessible
	site-topography	even, uneven			even, uneven
	site-stability	stable	stable	stable	stable unstable
	headroom	no	no	no	no
	surface-restraints	no	no	no	no
	development	undeveloped	undeveloped developed	undeveloped developed	undeveloped developed
	subsurface-restraints	no	yes	yes	no
construction-related-issues	time-requirement	long-term immediate	immediate	immediate long-term	long-term
	maintenance	no	yes	no	no
	material-durability	low	low	no	yes
	material-availability	yes	low	no	yes
	expertise-requirement	low	high	high	low
	labour-requirement	semi-skilled	skilled	skilled	unskilled
	equipment-availability	yes	yes	yes	no
economic-considerations	relative-cost	low	high	high	low
	contractor-availability	no	no	yes	no
environmental-impact	noise	low	low	low	low
	vibrations	low	low	low	low
	groundwater-pollution	low	low	low	low
	surface-water-pollution	high	low	high	low
tradition		no	no	no	no
geographic-limits		no	no	no	no

Note: bc = bearing capacity increase

REFERENCES

Adams, T. M., and Bosscher, P. J. (1995). Integration of GIS and knowledge-based systems for subsurface characterization. In Maher, M.L. & Tommelein, I (Eds), *Expert Systems for Civil Engineers: Integrated & Distributed Systems.*, New York: ASCE.

Adams, T.M., Christiano, P. and Hendrickson C. (1989). *Some expert system applications in geotechnical engineering.* Foundation Engineering: Current Principles and Practices, ASCE: New York, pp. 885-902.

Agrawal, T. M., Frost, J. D. and Chameau, J. L. (1994). Data Analysis and Modelling using an Artificial Neural Network, *Proc. 13th Conference of International Society for Soil Mechanics and Foundation Engineering,* New Delhi: New Delhi, Oxford & IBH Publ. Co., Vol.4, pp. 1441-1444.

Akawwi, E. and Al-Kharabsheh, A. (2000). *Lime stabilization Effects on geotechnical properties of Expansive Soil in Amman,* Jordan. EJGE, Vol. 5

Al Abo Omar, E. and Mangin, J.-C. (2003). A new generation of decision tools for improving building site productivity. *Civil Engineering and Environmental Systems,* Spon Press, Vol. 20, No. 3, pp. 163-184.

Alamgir, M., Miura, N., Poorooshasb, H. B. &. Madhav, M. R. (1996). Deformation analysis of soft ground reinforced by columnar inclusions. *Computers and Geotechnics*, Vol. 18 No. 4, pp. 267-290

Al-Homoud, A. S. and Al-Masri G.A. (1999). CSEES: an expert system for analysis and design of cut slopes and embankments, *Environmental Geology*; Ei Compendex-Elsevier. Vol. 39, No. 1, pp. 75-89.

Al-Homoud, A. S. & Tahtamoni W.W. (2000). SARETL: An expert system for probabilistic displacement-based dynamic 3-D slope stability analysis and remediation of earthquake triggered landslides, *Environmental Geology*, Geobase-Elsevier. Vol.39 No.8. pp. 849-874.

Al-Rawas, A. A, Hago, A. W., and Al-Sarmi, H. (2005). Effect of lime, cement and Sarooj (artificial pozzolan) on the swelling potential of an expansive soil from Oman. *Building and Environment*, 40, pp. 681 – 687.

Alenowicz, J. and Dembicki, E. (1991). Model tests on temporary road behaviour, *Proceedings of the International Reinforced Soil Conference organized by the British Geotechnical Society and held in Glasgow on 10 – 12 September 1990*, pp. 469 – 470.

Alexander, S. J., and Lawson, R. M. (1981). *Design for movement in buildings*. CIRIA Technical Note 107.

Allwood, R. J. (1989). *Techniques and applications of expert systems in the construction industry.* Publishers; Ellis Horwood Limited.

Almeida, M. S. S., Santa Maria, P. E. L., Martins, I. S. M, Spotti, A. P. and Coedlho, L. B. M. (2000). Consolidation of a very soft clay with vertical drains, *Geotechnique*, Vol. 50, No. 6, pp .633-643.

Alonso, E. E., Gens, A. & Lloret, A. (2000). Precompression design for secondary settlement reduction. *Geotechnique* 50, No 6, pp. 645- 656.

Altmeyer, W. T. (1955). Discussion of engineering properties of expansive clays. *Proceedings, American Society for Civil Engineers*. 81 (Separate No. 658): pp.17-19.

American Society for Testing Materials: Standard classification of soils for engineering purposes (Unified Soil Classification System). ASTM D2487-93.

American Society for Testing Materials. Expansion Index of Soils. ASTM D4829

Anderson, J. N. and Lade, P. V. (1981). The Expansion Index Test. The American Society for Testing and Materials.

Ando, Y., Tsubi, H., Yamamoto, M., Harada, K and Nozo, M. (1995). Recent soil improvement methods for preventing liquefaction, *Proceedings of Earthquake Geotechnical Engineering*. Balkema, Rotterdam, pp.1011-1016.

Andrus, R. D. and Chung, R. M. (1995). Cost-effective ground improvement for liquefaction remediation near existing lifelines, *Proceedings. 27th Joint Meeting of the U.S.-Japan Cooperative Program in Natural Resources Panel on Wind and seismic Effects,* Tsukuma, Japan, pp. 115-123.

ASCE. (1997). Ground Improvement, Ground Reinforcement, Ground Treatment; Developments 1987-1997, *Proceedings of sessions sponsored by the committee on Soil Improvement and Geosynthetics of The Geo-Institute of the American Society of Civil Engineers in conjunction with Geo-Logan '97.* Geotechnical Special Publication No. 69. Editor Schaefer, V.R..

Arnold, M. (1984). The genesis, mineralogy and identification of expansive soils. *Proceedings, 5th International Conference on Expansive Soils,* Adelaide, Australia, pp.32-36.

Arockiasamy, M., Radhakrishnan, N., Sreenivasan, G. and Lee, S. (1991). KBES Applications to the Selection and Design of Retaining Structures. *Proceedings. Geotechnical Engineering Congress,* Geotechnical Special Publication No. 27, (eds. McLean, F.G., Campbell, D.A. & Harris, D.W.), Boulder, Colorado: ASCE , pp. 391-402.

Arora, K. R. (1989). *Soil Mechanics and Foundation Engineering.* Standard Publishers Distributors, Nai Sarak, Delhi.

Atkinson, M. S. and Eldred, P. J. L. (1981) Consolidation of soil using vertical drains. Vertical Drains, *Third Geotechnique Symposium in Print,* pp.33-43.

Auld, F. A. (1985). Freeze wall strength and stability design problems in shaft sinking. *Proceedings, 4th International Symposium on Ground Freezing,* Sapporo, Eds S. Kinosita and M. Fukuda, Balkema, Rotterdam, Vol. pp. 345-349.

Bassett, R. H. (1991). Model and analytical comparisms of the behaviour of reinforced embankments on soft foundations. *Proceedings. of the International Reinforced Soil Conference organized by the British Geotechnical Society and held in Glasgow on 10 – 12 September 1990,* pp. 461 – 467.

Baumann, V. and Bauer, G. E. A. (1974). The performance of foundation on various soils stabilized by vibrocompaction method. *Canadian Geotechnical journal,*. Vol. 11, pp.509-530

Bell, F.G. (1978): *Foundation Engineering in difficult ground,* Butterworth publishers, Inc, Woburn, Massachusetts..

Bell, F. G. (1983). *Engineering properties of soils and rock.* Second Edition. Butterworths, London..

Bell, F. G. (1993*). Engineering Treatment of Soils.* E & FN SPON, London. 302p

Bergado, D. T., Balasubramaniam, A. S., Lo, K. H; Shivashankar, R.; Sampaco, C. L, and Alfaro, M. C. (1991). Interaction of steel geogrids and low-quality, cohesive-frictional backfill and behaviour of mechanically stabilized earth (MSE) wall on soft ground. In Balasubramaniam , A. S., Honjo, Y., Bergado, D. T., Phien-Wej, N., Indraratna, B., and Prinya Nutalaya(Eds) *Developments in Geotechnical Aspects of Embankments, Excavations and Buried Structures*., Balkema, Rotterdam, pp. 483-497.

Bergado, D. T., Chai, J. C, Miura, N. and Balasubramaniam, A. S. (1998). PVD improvement of soft Bangkok clay with combined vacuum and reduced sand embankment preloading. *Journal of Geotechincal Engineering,* Vol. 29, No. 1, pp. 95 – 122.

Bergado, D. T., Manivannan, R. and Balasubramaniam, A. S. (1996a). Proposed criteria for discharge capacity of Prefabricated Vertical Drains. *Geotextiles and Geomembranes,* Elsevier, Vol. 14, pp. 481 – 505.

Bergado, D. T., Anderson, L. R., Miura, N. and Balasubramaniam, A. S. (1996b). *Soft ground improvement in lowland and other environments.* ASCE Press, New York.

Bergado, D. T., Sampaco, C. L., Alfaro, M. C., Shivashankar, R. and Balasubramaniam, A. S. (1991). Mechanically stabilized earth (MSE) and other ground improvement techniques for infrastructure constructions on soft and subsiding ground. In Balasubramaniam , A. S., Honjo, Y., Bergado, D. T., Phien-Wej, N., Indraratna, B., and

Prinya Nutalaya (Eds), *Developments in Geotechnical Aspects of Embankments, Excavations and Buried Structures,*. Balkema, Rotterdam. pp. 461-482.

Bjerrum, L. (1963). Allowable settlement of structures. *Proceedings 3rd European Conference on Soil Mechanics and Foundation Engineering,* Wiesbaden.

Bo, M. W., Choa, V. and Zeng, X. Q. (2001). Laboratory investigation on electro-osmosis properties of Singapore marine clay. Soils and Foundations, *Japanese Geotechnical Society,* Vol. 41 No. 5, pp. 15-23.

Boardman, D. I., Glendinning, S. and Rogers, C. D. F. (2001). Development of stabilization and solidification in lime-clay mixes. *Géotechnique,* Vol. 50, No. 6, pp. 533 – 543.

Bowles, J.E. (1988). *Foundation analysis and design,* 4th Edition, McGraw-Hill, Inc, New York..

Brenner, R. P., Nutalaya, P., Chilingarian, G. V. &Robertson, J. O. (Jnr). (1981). *Engineering Geology of Soft Clay.* In Brand E. W and Brenner R. P Eds Soft Clay Engineering; Developments, Geotechnical Engineering 20.., Elsevier, pp. 159-238.

British Standards Institution, BS 1377:1975. *Methods of test for soil for civil engineering purposes.*

British Standards Institution. (1981). *Code of practice for site investigations, BS 5930:1981.*

British Standards Institution. (1986). *Code of practice for foundations, BS 8004:1986..*

Buchanan, B., Boechtal, R., Bennett, J., Clancey, W., Kulikowski, C., Mitchell, T., and Waterman, D. A. (1983). *Constructing an expert system,* In: Building Expert Systems, Eds; Hayes–Roth, D.A. Waterman and D. B. Lenat. Addison-Wesley, Reading, MA.

Buchanan, B.G. and Shortliffe, E.H. (1984). *Rule-based expert systems: The MYCIN experiments of the Stanford Heuristic Programming Project,* Addison-Wesley; Reading, MA.

Building Research Establishment. (1980). *Low-rise buildings on shrinkable clay soils: Part I.* Digest No 240, HMSO, UK.

Burland, J. B., and Wroth, C. P. (1975). Settlement of buildings and associated damage. *In Proceedings of a Conference on Settlement of Structures*, Cambridge, pp. 611-654.

Carter, M. and Bentley, S. P. (1991). *Correlations of soil properties.* Pentech Press, London.

Carter, M. and Symons, M. V. (1989). *Site investigations and foundations explained.* Pentech Press, London.

Casagrande, L., Wade, N., Wakely, M. and Loughney, R. (1981). Electro-osmosis projects, British Columbia, Canada, *Proceedings of the 10th International Conference on Soil Mechanics and Foundation Engineering,* Stockholm, 15–19 June 1981, Publ: A. A. Balkema, Rotterdam, V3, pp. 607–610.

Chahine, J.R. and Janson, B.N. (1987). Interfacing Databases with Expert Systems: a Retaining Wall Management Application, *Microcomputers in Civil Eng*ineering, 2, 1, pp. 19-38.

Chameau, J-L. and Santamarina, J.C. (1989). *Knowledge-Based System for soil improvement. Journal of Computing in Civil Engineering,* ASCE, 3, 3, pp. 253-267.

Charles, J. A. (2002). Ground improvement: the interaction of engineering science and experience-based technology. *Géotechnique* 52, No. 7, pp. 527-532.

Charles, J. A., Burford, D. and Watts, K. S. (1981). Field studies of the effectiveness of dynamic consolidation. *Proceedings 10th ICSMFE,* Stockholm, 3, pp. 617-622.

Chen, F.H. (1988). *Foundations on expansive soils.* Elsevier, Amsterdam.

Chi, B. P. L., Yang, J.-S. (1985). Chemical grouting in Taipei basin. *Proceedings, 11th International Conference on Soil Mechanics and Foundation Engineering,* Rio de Janeiro, Vol. 2, pp. 1347- 1350.

Choa, V. (1989). Drains and vacuum preloading pilot test *Proceedings. XII ICSMFE,* 2, 1347-1350.

Chorafas, D.N and Legg S.J. (1988). *The Engineering Database*, Computer-Aided Engineering Services, Butterworths..

Christian, J. T., Ladd, C. C. and Baecher, G. B. (1994). Reliability applied to slope stability analysis. *Journal of Geotechnical Engineering*, ASCE, 1994, 120(12), pp. 2180-2207.

Chu, J., Yan, S. W., & Yang, H. (2000). Soil improvement by the vacuum preloading method for an oil storage station. *Geotechnique,* Vol. 50. No 6, pp. 625 – 632.

Chuang, P.H. (1995). Use of fuzzy sets for evaluating shear strength of soils. *Computers and Geotechnics,* Vol.17, Elsevier, pp. 425-446.

Chung, P.W.H and Kumar B. (1987). Knowledge elicitation methods: A case study in structural design. *The Application of Artificial Intelligence Techniques to Civil Engineering;* Ed. B.H.V Toppings; CIVIL-COMP Press.

Citrenbaum, R., Geissman, J. R. and Schultz, R. (1990). Selecting a Shell, Expert Systems A Software Methodology for Modern Applications, IEEE Computer Society Press, Reprint Collection (Ed. Raeth, P. G.), IEEE Computer Society Press, California, pp. 52-61.

Coduto, D. P. (1999). *Geotechnical Engineering; Principles and Practices.* Prentice-Hall, Inc, New Jersey.

Coenen, F. and Bench-Capon, T. (1993). *Maintenance of Knowledge based Systems: Theory, Tools and Techniques.* Academic Press, London.

Consoli, N. C. and Thome, A. (2001). Discussion of Rogers et al. "Lime modification of clay soils for construction expediency". *Geotechnical Engineering*, 149, (3), pp. 201-202.

CUR (1996). *Building on soft soils; Design and construction of earth structures on and into highly compressible sub soils of low bearing capacity,* Centre for Civil Engineering Research and Codes, A.A.Balkema.

Das, B.M. (1990). *Principles of foundation engineering,* 2nd Edition, PWS-Kent Publishing Company, Boston, Massachusetts, pp. 174-179, 200.

Davey-Wilson, I.E.G. (1991). Geotechnical laboratory test simulation using AI techniques. *Artificial Intelligence and Civil Engineering.* Ed. Topping, B.H.V., Edinburgh: Civil-Comp Press, pp. 119-124.

Davey-Wilson, I.E.G. and Mistry, K. (1995). An intelligent database to predict geotechnical parameters. Developments in Artificial Intelligence for Civil and Structural Engineering. Ed. Topping, B.H.V., Edinburgh: Civil-Comp Press, pp. 105-111.

Davis, C. A., and Roux, R. F. (1997). *Case Study: Stone Columns for controlling differential settlement.* In Schaefer, V. R, (Ed), Ground Improvement, Ground Reinforcement, Ground Treatment Developments 1987-1997, ASCE, Geotechnical Special Publication No.69, pp. 444-456.

Davis, C. A., Roux, R. F., and Plumb, C. C. (1994). Rowena Tank Geotechnical and Foundation Report, Report AX 451-2, Department of WATER AND Power, City of Los Angeles.

De Wolf, P., Carpentier, R., Allert, J., and De Rouck, J. (1983). Ground improvement for the construction of the new outer harbour at Zeebrugge, Belgium, *Proceedings of the* *eight European Conference on Soil Mechanics and Foundation Engineering*; Helsinki; 23-26 May 1983, Edited by H.G Rathmayer & K.H.O. Saari, Vol.2, pp. 827-832.

Department of The Army (1999). *Engineering and design guidelines on ground improvement for structures and facilities,* U.S. Army Corps of Engineers, Washington, DC, Engineering Technical Letter (ETL) No. 1110-1-185.

Departments of The Army and The Air Force (1995). *Engineering use of geotextiles,* Joint Departments of the Army and Air Force, Technical Manual, TM 5-818-8/AFJMAN 32-1030.

Derbyshire, E. (2001). Geological Hazards in loess terrain, with particular reference to the loess regions of China. *Earth-Science Reviews* Vol. 54, pp. 231-260.

Diaz-Rodriguez, J. A., Lozano-Santa Cruz, R., Davila-Alcocer, V. M and Giron, P. (1998). Physical, chemical and mineralogical properties of Mexico City sediments: a geotechnical perspective. *Canadian Geotechnical Journal,* 35, pp. 600-610.

Dibiagio, E. and Myrvoll, F. (1981). Field instrumentation for soft clay. In Brand, E.W and Brenner, R.P, (eds) Soft clay engineering, Elsevier, Amsterdam

Dodagoudar, G. R. and Venkatachalam, G., (2000). Reliability analysis of slopes using fuzzy sets theory. *Computers and Geotechnics,* Elsevier, Vol. 27, pp. 101-115.

Duncan J. M. (1996). Sate-of-the-art: Limit equilibrium and finite – element analyses of slopes, *Journal of Getechnical Engineering.* Vol. 122 No.7, pp. 577-596.

Edil, T.B. (1983). *Improvement of peat: A case study.* In Rathmayer H.G. & Saari K.H.O (eds) Proceedings of the Eight European Conference on Soil Mechanics and Foundation Engineering; Helsinki; 23-26 May 1983, Vol.2, pp. 739-744.

Edwards, J. S. (1991). *Building Knowledge-Based Systems towards a methodology.* Pitman Publishing.

Elton, D. J., Juang C. H., Sukumaran B. (1995). *Liquefaction susceptibility evaluation using fuzzy sets. Soils Foundations*, Vol. 35, No 2, pp. 49-60.

Elton, D. J., Juang, C. H. and Lin, P.-S. (2000). Vertical capacity of piles using fuzzy sets. *Civil Engineering and Environmental Systems*, Overseas Publishers Association, N.V Malaysia, Vol. 17, pp. 237-262.

Ericsson, K. A. and Simon, H. A. (1980). *Verbal reports as data.* Psychological Review, 87, 215-251.

Ericsson, K. A. and Simon, H. A. (1984). *Protocol analysis.* Cambridge, Mass.: M.I.T. Press.

Esrig, M. L and Bachus, R. C. (Editors) (1991). *Deep Foundation Improvements: Design, Construction, and Testing,* ASTM STP 1089, Philadelphia, PA.

Eurocode 7: Geotechnical design Part 1: General rules – (together with United Kingdom National Application Document, DD ENV 1997-1:1995.

Fang, H. (1991). *Foundation Engineering Handbook,* 2nd Edition. Van Nostrand Reinhold, New York.

Faure, R.M., Mascarelli, D., Zelfani, M., Chaveriat L., Gandar, J. and Mosuro, O. (1991). XPENT: An expert system for slope stability. *Artificial Intelligence and Civil Engineering,* Ed. B.H.V. Topping; CIVIL-COMP LTD, pp. 143-147.

Faure, R.M., Mascarelli, D., Vaunat, J., Leroueil, S. and Tavenas, F. (1995). Present state of development of XPENT, Expert-System for Slope Stability Problems. *In Bell, D.H (ed), Proceedings 6th International. Symposium on Landslides,* Christchurch Rotterdam: Balkema, pp. 1671-1678.

FHWA (1983). Design and construction of Stone Columns Vol. 1, US. Department of Transportation, Federal Highway Administration; Report No. FHWA/RD-83/026

FHWA. (1995). Geotechnical Engineering Circular No. 1, Dynamic Compaction, U.S Department of Transportation, Federal Highway Administration, Publication No. FHWA-SA-95-037.

Feng, T-W, Lee, J-Y. and Lee, Y-J. (2001). Consolidation behaviour of a soft mud treated with small cement content. *Engineering Geology*, Vol. 59, pp. 327-335.

Flodin, N. and Broms, B. (1981). Historical development of civil engineering in soft clay. In Brand E. W and Brenner R. P (eds) Soft Clay Engineering; Developments in Geotechnical Engineering 20, Elsevier, pp. 29-156.

Fredlund, M. D., Sillers, W. S., Fredlund, D. G. and Wilson, G. W. (1996). Design of a knowledge-based system for unsaturated soil properties. *3rd Canadian Conference on Computing in Civil and Building Engineering,* Montreal, Quebeck, Aug 26-28.

Gaines, B. R. and Shaw, M. L. G. Eliciting Knowledge and Transferring it effectively to a Knowledge-Based System. (**http://ksi.cpsc.ucalgary.ca/articles/KBS/KSS0**

Gallaire, H., Minker J., and Nicholas J.M. (1984). Logic and database: a deductive approach, *ACM Computing Surveys* Vol. 16 No.2 , pp. 153-185.

Gangopadhyay, S., Gautam, T. R. and Gupa ,A.S. (1999). Subsurface characterization using Artificial Neural Networks and GIS. *Computing in Civil Engineering,* ASCE, Vol. 13, and No.3, pp. 153-161.

Giarratano, J. and Riley, G. (1998). *Expert Systems, Principles and Programming*; PWS-KENT Publishing Company, Boston.

Gibbs, Harold J. (1969), Discussion of Holtz, W.G. "The engineering problems of expansive clay subsoils". *In Proceedings of the Second International Research and Engineering Conference on Expansive Clay Soils,* Texas A&M Press, pp. 478-479.

Gill, W. R., and Reaves C. A. (1957). Relationships of Atterberg limits and cation-exchange capacity to some physical properties of soil. Soil Science Society. Am. Proc. 1957, 21, 491-494.

Gillete, D.R. (1991). An expert system for estimating soil strength parameters. *Proceedings Geotechnical Eng. Congress in Geotechnical Special Publication,* Ed. F.G. Mclean, D.W.A Campbell & D.W Harris. ASCE, Boulder, Colorado. Vol. 1 No 27, pp. 276-287.

Giolas, A. and Toll D.G. (1999). A Knowledge-based system for correlations using object hierarchies, *Computers and Geotechnics*. Elsevier. Vol. 25, pp. 123-143.

GNK Hayward Baker, Inc. (1993). Ground Modification Seminar Notes.

Goh, A.T.C. (1999). Soil laboratory data interpretation using Generalized Regression Neural Network. *Civil Engineering and Environmental Systems*. Overseas Publishers Association, N. V, Malaysia. Vol. 16, pp. 175-195.

Goh, A.T.C. (2000). Search for critical slip circle using Genetic Algorithms. *Civil Engineering and Environmental Systems.* Overseas Publishers Association, N. V, Malaysia. Vol. 17, pp. 181-211.

Gonzalez, A. J., and Dankel, D. D. (1993). *The engineering of Knowledge-Based Systems*. Prentice Hall.

Gourley, C. S., Newill, D. and Schreiner, H. D. (1993). Expansive soils: TRL's research strategy. *In Proceedings of the First International Symposium on Engineering Characteristics of Arid Soil*, City University, London, 5-8 July 1993.

Gouvenot, D. (1998). State of the art in European grouting. *Ground Improvement*, Vol. 2, pp.51-67.

Graham-Jones, P. J. and Mellor B.G. (1995). Expert and Knowledge-Based Systems in Failure analysis. *Engineering Failure Analyses*. Elsevier. Vol. 2, No. 2, pp. 137-149.

Grant, R., Christian, J. T. and Vanmarcke, E. H. (1974). Differential settlement of buildings. *Journal of Geotechnical Engineering*, Div, ASCE, Vol. 100, No. GT9, pp. 973-992.

Hadipriono, F. C. and Wolfe, W. E. (1991). Reparability assessment of damaged foundations. *Artificial Intelligence and Civil Engineering.* Ed. B.H.V. Topping. CIVIL-COMP PRESS, pp. 137-141.

Haeri, S. M., Noorzad, R. and Oskoorouchi, A. M. (2000). Effect of geotextile reinforcement on the mechanical behavior of sand. *Geotextiles and Geomembranes,* Elsevier, Vol. 18, pp. 385-402.

Hamadto, M.E.M. (2000). 'Expansive soil behaviour and the development of a knowledge-based system associated with foundations in expansive soils', PhD Thesis, Heriot-Watt University, Edinburgh.

Hansbo, S., Jamiolkowski, M and Kok, L. (1981). Consolidation by vertical drains. Vertical Drains: *Third Geotechnique Symposium in print,* pp, 45-66.

Hart, A. (1985). Knowledge elicitation: Issues and methods, *Computer Aided design,* Vol. 17 No. 9, pp. 455-462.

Harvey, J. A. F. (1997). Vacuum drainage to accelerate submarine consolidation at Chek Lap Kok, Hong Kong. *Ground Engineering,* July, pp. 34 – 36.

Head, K. H. (1982). *A manual of soil laboratory testing.* Pentech Press (London).

Hirokane, M., Mikami I., Yagashira, K., Kawano, K. and Ohmori,S. (1993). Knowledge acquisition and evaluation for selection of slope-protection structures. *Knowledge-based Systems for Civil and Structural Engineering.* Ed. B.H.V.Topping, CIVIL-COMP Press, pp. 161-169.

Hitcher, P.Y. and Michali A. (1996). Identifying soil parameters by means of laboratory and in situ testing, *Computers and Geotechnics,* Elsevier, Vol. 25, pp. 153-170.

Holsapple, C. and Whinston A. (1995). Business Expert Systems; Homewood, IL: Irwin.

Holtz, R. D. (1990). Design and construction of geosynthetically reinforced embankments on very soft soils; Performance of reinforced soil structures. *In McGowen Alan, Yeo K. & Andrawes* (eds), *Proceedings International Reinforced Soil Conference Organized by the British Geotechnical Society and held in Glasgow on 10th -12th Sept. 1990,* Thomas Telford, London, pp. 391-402.

Holtz, R. D. (1975). Recent developments in reinforced earth. *Proceedings of the 7th Scandinavian Geotechnical Meeting,* Published by Polyteknisk Forlag, 281-291.

Holtz, R. D. and Massarch, K. R. (1976). Improvement of the stability of an embankment by piling and reinforced earth., *Proceedings of the VI European Conference on Soil Mechanics and Foundation Engineering,* Vol. 1.2, pp. 473-478.

Holtz, W. G. (1969). Volume changes in expansive clay soils and control by lime treatment, *In Proceedings of the Second International Research and Engineering Conference on Expansive Clay Soils,* Texas A&M Press, pp. 157-173.

Huang, Y.-T., and Siller T. J. (1997). Fuzzy Representation and Reasoning in Geotechnical Site Characterization, *Computers and Geotechnics,* Elsevier. Vol. 21, No. 1 pp. 65-86.

Hughes, J. M. O. and Withers, N. J (1974). *Reinforcement of soft cohesive soils with stone columns. Ground Engineering,* Vol. 7, No. 3, pp. 42-49.

Hunt, R. E. (1986). *Geotechnical engineering analysis and evaluation.* McGraw-hill, USA.

Hutchinson, P.J., Rosenman, M.A. and Gero, J.S. (1987). RETWALL: An expert system for the selection and preliminary design of earth retaining structures. *Knowledge-based Systems,* 1, 1, pp. 11-23.

ICBO (1997).Uniform Building Code, International Conference of Building Officials, Whittier, CA.

ICI. (1990). *Lime Stabilisation.* Institution of Civil Engineers, Second Ed. 42p.

IS: 1904-1978. The Indian Code of Practice for Structural Safety of Building Foundations.

Izadi, M., Puzenat, Y., Chambon, R. and Flavigny, E. (1995). An expert system for design of shallow foundations. *Developments in Artificial Intelligence for Civil and Structural Engineering.* B.H.V.Topping (ed). CIVIL-COMP PRESS. pp. 121-127.

Jarret, P. M.(ed) (1982). *Testing of peats and organic soils.* A symposium sponsored by ASTM Committee D-18 on soil and rock. Toronto, Canada, 23 June 1982. ASTM Special Technical Publication 820.

Jessberger, H. L. and Beine, R. A. (1981). Heavy Tamping: Theoretical and Practical Aspects, *In: Proceedings of the Tenth International Conference on Soil Mechanics and Foundation,* Balkema, Vol. 3, pp. 695-699.

Jones, D. E and Holtz, W. G. (1973). *Expansive soils – the hidden disaster.* Civil Eng., ASCE 43 (8), pp. 49-51.

Jones, D. E. and Jones, K. A. (1987). Treating expansive soils. *Civil Engineering Magazine*. ASCE 43:11

Joshi, R. C., Natt, G. S. and Wright, P. J. (1981). Soil Improvement by Lime-Fly Ash Slurry Injection. *Proceedings of the Tenth international Conference on Soil mechanics and Foundation Engineering, Stockhom 15-19 June 1981.* Publications Committee of X. ICSMFE (eds), Vol.3, pp. 707-712.

Juran, I. and Levy, O. (1997). International Knowledge Database for Ground Improvement Technologies (IKDGIT). Sponsored by ISSMGE TC-17, The Federal Highway Administration and Polytechnic University, Brooklyn, NY. Internet Source: http://tc17.poly.edu/ikd.htm. (viewed 27/09/01).

Kaczyński, R., Grabowska-Olszewska, B. (1997). Soil mechanics of the potentially expansive clays in Poland, *Applied Clay Science,* 11, pp.337 – 355.

Kamon, M. and Bergado, D. T. (1991). Ground improvement techniques. *In: Proc. 9th Asian Regional Conference on Soil Mechanics and Foundation Engineering*, Bangkok, Vol. 2, pp. 526-546.

Kariuki, P. C; and van der Meer, F. (2004). A unified swelling potential index for expansive soils; *Engineering Geology*, Vol. 72, pp. 1-8.

Karol, R.H., (1982). Chemical grouts and their properties. *In Grouting in Geotechnical Engineering, Speciality Conference*, New York, pp. 359 -377.

Kézdi, Á. and Réthati, L. (1998). *Handbook of Soil Mechanic*, Vol. 3. Soil Mechanics of Earthworks, Foundations and Highway Engineering, Elsevier.

Kidd, A. L. (1987). *Knowledge acquisition; An introductory framework. In* Kidd, A. L (ed), *Knowledge Acquisition for Expert Systems,* A Practical Handbook. Plenum Press, New York, pp.1-16.

Kim, C. Y, Bae, G. J., Hong, S. W., Moon, H. K. and Oh, M. Y. (1999). A Neural network expert system developed for predicting the ground settlement and the damage assessment of adjacent structures due to tunnel excavation. *in* Chung, J. S, Matsui,T and Koterayama, W *(eds) Proceedings 1999 Ninth International Offshore Engineering Conference* (Vol. 1), Brest, France. Pub. Int. Soc. of Offshore and Polar Engineers. Eds.

Kimura, M., Nishizawa, T., Kotera, H., & Katakura, N. (2000). Improvement of soft ground using solidified coal ash and its effects on the marine environment, *Journal of Hazardous Materials*, Elsevier; Vol. 76, pp. 285-299.

Kitsugi , K. and Azakami, H. (1982). Lime-column techniques in the improvement of clay ground. *Symposium on Soil and Rock Improvement Techniques including Geotextiles, Reinforced Earth and Modern Piling Methods*, 29 Nov - 3 Dec.

Klein, J. (1989). State of the art: engineering design of shafts, in. Jones R. H and. Holden, J. T, (eds)., *Proceedings of the 5th International Symposium on Ground Freezing, Nottingham,* Eds., Balkema, Rotterdam, Vol. 11, pp. 235-244.

Knight, K. (1963). The origins and occurrence of collapsing soils. *Proceedings of the Third Regional Conference for Africa on Soil Mechanics and Foundation Engineering,*, Salisbury, South Rhodesia, Vol. 1, pp.127-130.

Koerner, R. M. (1985). *Construction and geotechnical methods in foundation engineering;* International Student Edition. McGraw-Hill, Inc, NY. 496p.

Koutsoftas, D. C, Foot, R. and Handfelt, L. D. (1987). Geotechnical investigations offshore Hong Kong. *Journal of Geotechnical Engineering*. Div., ASCE 111, No. 2, pp.87-105.

Lacasse, S. and Nadim, F. (1996). *Uncertainties in characterizing soil properties. Uncertainties in the Geologic Environment: From Theory to Practice,* Eds. C. D. Shackleford, P. P. Nelson and M. J. S. Roth. ASCE, Madison, WI, pp. 49-75.

Lambe, T. W. (1962). "*Soil Stabilization,*" *Foundation Engineering*, Leonards, G. A.(ed), McGraw Hill, New York.

Landva, A.O., Korpijaakko, E.O., and Pheeney, P.E. (1983). "*Geotechnical Classification of Peats and Organic Soils.*" *Testing of Peats and Organic Soils,* ASTM, Special Technical Publication No.820, P.M. Jarrett, Ed., American Society for Testing and Materials, pp. 37-51.

Liebowitz, J. (1995). Expert Systems: A short Introduction, *Engineering Fracture Mechanics,* Elsevier, Pergamon. Vol. 50, No. 5/6, pp.601-607.

Liu, T.S. (1985). *Loess and the environment.* Science Press, Beijing, (Ed).

Liu, T.S., Wang, T.M., Wang, K. L., Wen, C.C. (1996). *Loess on the middle Reaches of the Yellow River*. Science Press, Beijing.

Lockwood, S. and Chen, Z. (1995). Knowledge validation of engineering expert systems. *Advances in Engineering Software*, Elsevier, 23, pp. 97-104.

Lok M. (1987). LOGS: A prototype expert system to determine stratification profile from multiple boring logs, Master's thesis, Carnegie Mellon University, Pittsburgh.

Lopez-Lara, T., Zepeda-Garrido, J. A. and Castario, V. M. (1999). A comparative study of the effectiveness of different additives on the expansion behaviour of clays. EJGE, Vol. 4.

Luger, G. F. and Stubblefield W. A. (1999). *Artificial intelligence: Structures and Strategies for complex problem solving*, Addison-Wesley, Longman Inc. USA..

Majes, B. and Battelino, D. (1985). Effect of surface reinforcing of soft soils, *Proceedings of the Eleventh International Conference on Soil Mechanics and Foundation Engineering*, San Francisco, 12-16 Aug. 1985, PUBLICATIONS Committee of XI ICSMFE (ed), Balkema, Vol. 3, pp.1729-1734.

Mascarelli D., Faure R.M. and Kastner R. (1992) Anatomie d'un projet à base de connaissances XPENT, système de travail en ingénierie des pentes. *In: Geotechnique et Informatique, Proc. Int. Conf. on Geotechnics and Computers,* Paris: Presses de l'École Nationale de Ponts et Chaussées, pp. 587-598.

May, I. M., Mathew, R. G. S. and Alwani, M. M. (1997). The validation of a knowledge based system for the diagnosis of the causes of cracking in masonry structures. *Civil Engineering Systems,* OPA, Amsterdam, Vol. 14, pp.269-289.

Mayne, P.W., Jones, J. S and Dumas, J.C. (1984). Ground response to dynamic compaction. *Journal of Geotechnical Engineering*, ASCE, Vol. 110, No. 6, pp.757-774.

McCarthy, D. F. (1993). *Essentials of Soil Mechanics and Foundations*: Basic Geotechnics, Prentice Hall. 4th Ed.

McCormack, D. E., and Wilding, L. P. (1973). Soil properties influencing swelling in Canfield and Geeburg soils. Soil Science Society. America. Proceedings. 39, pp. 496-502.

McGown, A. and Hughes, F. H. (1981). Practical aspects of the design and installation of deep vertical drains . In *Vertical Drains, Third Geotechnique Symposium in print.*

McKenna, J. M, Eyre W. A and Wostenholme D. R. (1976). Performance of an embankment supported by stone columns in soft ground. Ground treatment by deep compaction, The Institution of Civil Engineers, London, pp. 51-59.

McKittrick, D. P. (1979). Reinforced earth: application of theory and research to practice, *Ground Engineering*, Vol. 12, No. 1, pp. 19 – 31.

Menard, L. and Broise, Y. (1975): Theoretical and practical aspects of dynamic consolidation, *Geotechnique*, Vol. 25, pp. 3-18.

Mettier, K., (1985).Ground freezing for the construction of the Milchbruch tunnel in Zurich, Switzerland, in Kinosita, S. and Fukuda, M. (eds) *Proceedings 4th International Symposium on Ground Freezing*, Sapporo, , Balkema, Rotterdam, Vol.1, p 345.

Meyerhof, G. G. (1947). The settlement analysis of buildings frames. *Structural Engineer* 25 (9), 369p.

Miao, L., Liu, S. and Lai, Y. (2002). Research of soil-water characteristics and shear strength features of Nanyang expansive soil. *Engineering Geology*. Elsevier, Vol. 65, pp 261-267.

Mitchell, J. K. (1993). *Fundamentals of soil behaviour*, 2nd Edition. John Wiley & Sons, Inc. Canada, p. 18-40.

Motamed, F., Salazar, G. and Dandrea, R. (1991). An Expert System for Preliminary Ground Improvement Selection. *In: Proceedings, Geotechnical Engineering Congress, Geotechnical Special Publication No. 27*, (eds. McLean, F.G., Campbell, D.A., Harris, D.W.), Boulder, Colorado: ASCE, pp. 379-390.

Moula, M. and Toll D.G. (1993). Representing geotechnical knowledge: Soils and field tests. *Knowledge-based Systems for Civil and Structural Engineering*. Ed. B.H.V. Topping; CIVIL-COMP PRESS. pp. 171-182.

Moula, M., Toll D.G. and Vaptismas N. (1995). Knowledge-based systems in geotechnical engineering. *Geotechnique*. Vol. 45, No. 2, pp. 209-221.

Muir Wood, D., Hu, W. and Nash, D. F. T. (2000). Group effects in stone column foundations: model tests. *Geotechnique*, Vol. L, No. 6, pp. 689 –697.

Mullarkey, P.W. (1986). A geotechnical KBS using fuzzy logic. In Sriram D. and Adey R.(eds), *Applications of A .I. in Engineering Problems.* Springer-Verlag, Vol. 2, pp. 847-859.

Mullarkey, P.W. and *Fenves S.J. (1986)*, Fuzzy logic in a geotechnical knowledge based system: CONE, Civil Eng. Systems, 3, 2, pp. 58-81.

Munfakh, G. A. (1997). *Ground Improvement Engineering - the State of the US Practices: Part 1; Methods,* Ground Improvement, Vol.1, pp. 193-214.

Munfakh, G. A. (2003). Ground improvement in transportation projects: from old versions to innovative applications. *Ground Improvement,* Vol.7, No. 2, pp. 47-60.

Munfakh, G. A, and Wylie, D. C. (2000). Ground improvement engineering-uses and selection, *Proceedings, An International Conference on Geotechnical and Geological Engineering, GeoEng2000,* 19-24 November 2000, Melbourne Australia.

Muntohar, A. S. (1999). Effect of lime and rice husk ash on the behaviour of soft clay, *Regional Seminar at Islamic University of Indonesia,* Sept. 4th 1999. Yogyakarta, Indonasia.

Muntohar, A. S., and Hantoro, G. (2000*). Influence of rice husk ash and lime on engineering properties of a clayey sub-grade*. EJGE, Vol. 5.

Nagaraj, T. S. and Miura, N. (2001). *Soft clay behaviour; Analysis and Assessment.* A.A. Balkema, Rotterdam.

Najjar, Y. M, Basheer, I.A. and Naouss, W. A. (1996). On the identification of compaction characteristics by Neuronets. *Computers and Geotechnics*, Vol. 18, No. 3, Elsevier, pp. 167-187.

Najjar, Y. M., Basheer, I. A., Ali, H. E., and McRyenolds, R. L. (1999). Characterizing the swelling potential of soils via neuro-reliability approach. *Intelligent Engineering Systems Through Artificial Neural Networks*, ASME, Vol. 9, pp. 1201-1206.

Najjar, Y.M., Basheer, I. A. and Naouss, W. A. (1996). On the Identification of Compaction characteristics by neuronets. *Computers and Geotechnics*, Elsevier, Vol. 18, No. 3, pp. 167-187.

Nalbantoglu, Z. & Gucbilmez, E. (2001). Improvement of calcareous expansive soils in semi-arid environments. *Journal of Arid Environments*, Academic Press, 47, pp. 453-463.

Nash, D. F. T., Powell, J.J.M., and Lloyd, I.M (1992). Initial investigations of the soft clay site at Bothkennar, *Geotechnique*, 42, No. 2, pp. 163-181.

Nash, D. F. T. and Ryde, S. J. (2000). *Modelling consolidation accelerated by Vertical Drains in soils subject to creep. Geotechnique*, Vol. 50, No. 3, pp. 257 – 273.

Nawari, N. O., Liang, R. and Nusairat, J. (1999). Artificial Intelligence techniques for the Design and analysis of Deep foundations. Electronic Journal for Geotechnical Engineering. Paper 9909.

Nelson, J. D. and Miller, D. J. (1992). Expansive soils: Problems and Practice in Foundation and Pavement Engineering. John Wiley & Sons, Inc, New York.

Ni, S. H., Lu, P. C. and Juang, C. H. (1996). Fuzzy neural network approach to evaluation of slope failure potential. *Microcomputers in Civil Engineering*, Blackwell Publishers, Vol. 11, No. 1, pp. 59-66.

Nicholson, D. P. and Jardine, R. J. (1981). Performance of vertical drains at Queenborough bypass. Vertical Drains, *Third Geotechnique Symposium in print*, pp.67-90.

Nicholson, P. J. (1998). Cement Soil Mixing in Soft Ground, Internet Version, http:/gem.cive.uh.edu/content/conf_exhib/99_present/13.htm.

Nixon, I. K. (1982). The standard penetration test – a state-of-the-art report. *Proceedings European Symposium On Penetration Testing II*, Amsterdam, Vol. 1, pp 3-24

O'Keefe, R. and *O'Leary, D. (1993).* Expert system verification and validation: a survey and tutorial. Artificial Intelligence Review, 7, pp.3-42.

Oliphant, J. and Blockley D.I. (1989). Knowledge Based System: Advisor on the Selection of Earth Retaining Structures, Proceedings 4th International Conference. A.I. Techniques and Applications for Civil and Structural Engineering Computing, Edinburgh: Civil-Comp Press, pp. 253-262.

Oliphant, J., Ibrahim, J.A.R., and Jowit P.W. (1996). ASSIST: a computer-based advisory system for site investigations, Proceedings Institution of Engineers, Geotechnical. Engineering. Vol. 119, pp. 109-122.

Oliver, A. I., and Toll, D.G. (1995). An object-oriented approach to site investigation data management and interpretation, *Developments in Artificial Intelligence for Civil and Structural Engineering*. Ed. B.H.V. Topping. CIVIL-COMP PRESS, Edinburgh, pp. 89-95.

Owoc, M. L., Ochmanska, M. and Gladysz, T. (1999). *On principles of knowledge validation. In Validation and Verification of Knowledge Based Systems; Theory, Tools and Practice.* Eds. Vermesan, A. and Coenen, F. Kluwer Academic Publishers, pp.25-35.

Padfield, C. J., Sharrock, M. J. (1983). *Settlement of structures on clay soils.* CIRIA Special Publication 27. PSA Civil Engineering Technical Guide 38, 132p.

Parry, R. H. G. and Wroth, C.P. (1981). Shear Stress-Strain Properties of Soft Clays. In. Brand E. W. and. Brenner R. P.(eds) *Soft Clay Engineering: Developments in Geotechnical Engineering* Vol.20, Elsevier, pp. 311-364.

Payne, E. C. and McArthur, R. C. (1990). *Developing Expert Systems. A Knowledge Engineer's handbook for rules and objects.* John Wiley & Sons, New York.

Penumadu, D and Zhao, R. (2000). *Modelling drained triaxial compression behaviour of sand using ANN.* Geotechnical Special Publication, ASCE, No. 96, pp. 71-87.

Pham D.T and Pham P.T.N. (1999). Artificial intelligence in engineering, *International Journal of Machine Tools and Manufacture, Design Research and Application.* Pergamon Vol. 39, pp. 937-949.

Phillip, L., and Juran, I. (1995). "Texol: Material properties & Engineering performance", *Transportation Research Record, Soils Geology and Foundation.* Vol. No. 1474, pp. 3-13.

Pilot, G. (1981). Methods of improving the engineering properties of soft clay. *In* Brand E. W.. and Brenner R. P.(eds) *Soft Clay Engineering: Developments in Geotechnical Engineering,* Vol. 20. Elsevier, pp. 637-696.

Polshin, D. E. and Tokar, R. A. (1957). Maximum allowable non-uniform settlement of structures. *Proceedings, 4th International Conference on Soil Mechanics and Foundation Engineering*, London, Vol. 1, 402.

Poorooshasb, H. B. and Meyerhof, G. G. (1997). Analysis of the behaviour of Stone Columns and Lime Columns. *Computers and Geotechnics*, Elsevier, Vol. 20, No. 1, pp.47 – 70.

Popovics, H. (1978). Slag as an embankment material. *International Confrence on the use of By-products and Wastes in Civil Engineering* 2, pp. 319-324.

Priebe H. (1976) Abschatzunz des setzungsverhattens eines durch. stopverdichtung verbesserten baugrundes. Die Bautechnik, 53,. 160–162. as cited in Davis and Roux

(1997): Case Study :Stone columns for controlling differential settlement. Geotechnical Special Publication No.69, 444-456).

Qian, J.H. (1985). Dynamic Consolidation: From practice to theory. *In Proceedings: ICSMFE* {as cited in: Van Impe, W. F., De Cock, F., Van Der Cruyssen, J. P., and Maertens, J. (1997). Soil improvement experiences in Belgium: Part I. Overview and dynamic compaction. Ground Improvement, Vol. 1, pp. 147 – 155}.

Qian, J. H., Zhao, W.B., Cheung, W. B., Cheung, Y. K., & lee, P. K. (1992). The theory and practise of vacuum preloading. *Computers and Geotechnics*. Vol 13, pp.103 – 118.

Rahman, M. S., Wang, J., Deng, W. and Carter, J. P. (2001). A neural network model for the uplift capacity of suction caissons. *Computers and Geotechnics,* Elsevier, Vol. 28, pp. 269-287.

Rajasekaran, G., Murali, K. and Srinivasaraghavan, R. (1999). Microfabric, chemical and mineralogical study of Indian marine clays. *Ocean Engineering*, Pergamon, 26, pp. 463-483.

Ranga Rao, A.V. and Sundaravadivelu, R. (1999). A knowledge based expert system for design of berthing structures. *Ocean Engineering*, Pergamon, Vol. 26, pp 653-673.

Rashad, M.M., Yehia, N.A.B., Bazaraa, A.S. and Dessouki A.I. (1991). FOUNDCON: A conceptual model for the integrated knowledge-based CAD Systems for foundation design. *Artificial Intelligence and Civil Engineering*. Topping B.H.V (ed). CIVIL-COMP PRESS, pp. 125-135.

Rehak, D. R., Christiano, P. P and Norkin, D. D. (1985). SITECHAR: An expert system component of a geotechnical site characterization workbench. In Dym, C. L (ed): *Applications of Knowledge-based Systems to Engineering Analysis and Design.* . American Society of Mechananical Eng., New York, pp.117-133.

Rixner, J. J., Kraemer, S. R., and Smith, A. D. (1986).Prefabricated vertical drains, Vol. 1 (Eng'g. Guidelines), Federal Highway Administration, Report No. FHWA-RD-86/168, Washington D.C.

Rogers, C. D. F. and Glendinning, S. (1997). Improvement of clay soils in situ using lime piles in the UK, *Engineering Geology*, Elsevier, Vol. 47, pp. 243-257.

Rogers, C. D. F. and Glendinning, S., and Roff, T. E. J. (1997). Lime modification of clay soils for construction expediency. *Proceedings. Institution of Civil Engineers Geotechnical Engng*, 125, pp. 242-249.

Rosenman, M.A, Balachandran B.M and Gero J.S. (1989). *The place of Expert Systems in civil engineering;* Civil Engineering Systems decision making and problem solving. Vol. 6, Nos. 1 & 2 pp. 11-20.

Sabatini, P.J., Bachus, R.C., Mayne, P.W., Schneider, J.A. and Zettler, T.E. (2002). Evaluation of Soil and Rock Properties, Geotechnical Engineering Circular No. 5, FHWA Report No.FHWA IF-02-034..

Sabtan, A. A. (2005). Geotechnical properties of expansive clay shale in Tabuk, Saudi Arabia, *Journal of Asian Earth Sciences,* Elsevier, 25, pp. 747-757.

Saitoh, S., Suzuki, Y., and Shirai, K. (1985). Hardening of soil improved by deep mixing method. *In Proceedings of the Eleventh International Conference on Soil Mechanics and Foundation Engineering, San Francisco, 2-16 Aug. 1985,* Ed. PUBLICATIONS Committee of XI ICSMFE, Balkema, Vol. 3, pp. 1745-1748.

Santos Jr., E., Gleason, H. T. and Banks, S. B. (1997). BVAL: Probablistic Knowledge-base validation. *Proceedings of the AAAI Workshop on Verification and Validation of Knowledge-Based Systems*, pp. 13-22.

Schafer, W. M. and Singer, M. J. (1976). Influence of physical and mineralogical properties on swelling of soils in Yolo County, California. *Soil Science Society of America Journal* 40(4), pp.557-562.

Schlosser, F. (1990). Mechanically stabilized earth retaining structures in Europe, In: Design and performance of earth retaining Structures; Lambe P. C. and Hansen L. A (eds), ASCE Geotechnical Special Publication No. 25, pp. 347 – 378.

Schwab, E. F. and Pregl, O. (1978). *Incinerator refuse as fill material. International Conference on Use of By-products and Waste in Civil Eng'ng.* 2, pp. 429-436.

Shang, J. Q and Zang, J. (1999). *Vacuum consolidation of soda-ash tailings.* Ground Improvement, Vol. 3 No. 1, pp.169 – 177.

Shang, J. Q., Tang, M. and Miao, Z. (1998). Vacuum preloading consolidation of reclaimed land: a case study, *Canadian Geotechnical Journal,* Vol. 35, No. 5, pp. 740 – 749.

Siller, J. T. (1987). Expert Systems in Geotechnical Engineering. *Expert Systems for Civil Engineers: Technology and Applications,* Maher M.L (ed), New York: ASCE, pp. 77-84.

Skempton, A. W. and MacDonald, D. H. (1956). The allowable settlements of buildings. *Proceedings, Institution of Civil Engineers, Part III,* 5, pp.727-768.

Skempton, A. W. and Northey, R. D. (1952). Sensitivity of Clays. *Geotechnique,* Vol. 3, No. 1, pp. 40-51

Snethen, D. R. (1984). Evaluation of expedient methods for identification and classification of potentially expansive soils. *Proceedings 5th International Conference on Expansive Soils,* Adelaide, Australia, pp.218-221.

Söderblom, R. (1969). Salt in Swedish clays and its importance for quick clay formation. *Swedish Geotechnical Institute Proceedings,* 22, pp. 1 - 61.

Somerville, S. H. (1986). Control of groundwater for temporary works. CIRIA Report 113.

Sokpo, J. A., and Aluce, G. F. (2003). Artificial ground freezing – for environmental remediation. Technical Papers, Layne Christensen Geotechnical Construction Group. http://www.groundfreezing.com/artificial_ground_freezing.html, (23/10/03)

Sokpo. J. A. and Andersland, O. B. (2003) Frozen earth cofferdam design. Technical Papers, Layne Christensen Geotechnical Construction Group. http://www.groundfreezing.com/frozen_earth_cofferdam_design.html, (23/10/03)

Sorochan, E. A. (1991). Construction of buildings on expansive soils. *Geotechnika 5. Selected translations of Russian geotechnical literature*. Oxford & IBH Publishing Co. PVT.Ltd.

Sowers, G. F. (1962). Shallow foundations. Chapter 6 in Foundation Engineering. G. A Leonards (Ed.) McGraw-Hill, New York, pp.525-632.

Sowers, G. B. and Sowers, G. F. (1970). *Introductory soil mechanics and foundations*. 3rd Edition. New York, The Macmillan Company.

Spreeuwenberg. S. and Gerrits. R. (1999). A Knowledge-based tool to validate and verify an aion knowledge base: In Vermesan, A. and Coenen, F.(eds), *Validation and Verification of Knowledge Based Systems, Theory, Tools and Practice*: pp. 67- 78.

Storey V. C. and Goldstein R. C. (1988). A methodology for creating user views in database design. *ACM Transactions on Database Systems*. Vol. 13 No. 3 pp. 305-338.

Tanaka, H., Locat, J., Shibuya, S. and Shiwakoli, D. R. (2001). Characterization of Singapore, Bankok and Ariake clays. *Canadian Geotechnical Journal*, 38, pp.378-400.

Tang, M. & Shang, J. Q. (2000). Vacuum preloading consolidation of Yaoqiang Airport runway. *Geotechnique*, Vol. 50. No 6, pp. 613 – 623.

Terzaghi, K. (1943). *Theoretical Soil Mechanics*. John Wiley and Sons, New York.

Terzaghi, K., and Peck, R. B. (1967). *Soil Mechanics in Engineering Practice*. A Wiley International Edition.

The Japanese Geotechnical Society (eds). (1998). *Remedial measures against soil liquefaction: From investigation and design to implementation*. A.A Balkema, Rotterdam, Netherlands.

Toll D. G., Moula M., Oliver A. and Vaptismas N. (1992). A Knowledge Based System for interpreting site investigation information. *Geotechnique et Informatique, Proc. Int. Conf. on Geotechnics and Computers, Paris: Presses de l'École Nationale de Ponts et Chaussées*, pp. 607-614.

Toll, D.G. (1994). Interpreting site investigation data using a knowledge based system. *Proceedings, 13th Conference of International Society for Soil Mechanics and Foundation Engineering*, New Delhi: New Delhi, Oxford & IBH Publ. Co., Vol.4, pp. 1437-1440.

Toll D. G. (1995). The role of a knowledge-based systems in interpreting geotechnical information. *Geotechnique*. Vol. 45, No.3, pp. 525-531.

Toll D.G. (1996a). Artificial intelligence applications in geotechnical engineering; EJGE. http://geotech.civen.okstate.edu/ejge/ppr9608.

Toll D.G. (1996b). Artificial Intelligence Systems for Geotechnical Engineering with specific reference to ground Improvement; 10th European Young geotechnical Engineers' Conference, Izmir. Electronic Journal of Geotechnical Engineering. http://www.ins.edu.tr/10ygec.html

Toll, D.G. (1998). Representing geotechnical properties in a knowledge-based system; *Advances in Engineering Software*. Elsevier & CIVIL-COMP Ltd, Vol. 29, No. 7 – 9 pp. 627-636.

Toll, D.G., and Barr, R .J. (1998). A computer-aided learning system for the design of foundations. *Advances in Engineering Software*; Elsevier. Vol. 29, No. 7-9, pp. 637-643.

Toll, D.G., and Barr, R .J. (2000). A computer-aided learning system for the design of foundations. *Advances in Engineering Software*; Elsevier. Vol. 29, No. 7-9, pp. 637-643.

Toll, D.G. and Barr, R. J. (2001). A decision support system for geotechnical applications. *Computers and Geotechnics*; Elsevier. Vol. 28, pp. 575-590.

Toll, D. G. and Giolas, A. (1995). A Knowledge-Based System for estimation of geotechnical properties. *In Topping, B.H.V (ed) Developments in Artificial Intelligence for Civil and Structural Engineering*, Edinburgh: Civil-Comp Press, pp. 113-119.

Toll, D.G. and Giolas, A. (1998). Representing geotechnical properties in a Knowledge-Based system, *Advances in Engineering Software*, Vol. 29, No. 7-9, pp. 627-636.

Tomlinson, J. (1980). Foundation Design and Construction. 4th Edition. Pitman Advanced Publishers, London, pp. 133, 138-139.

Tonon F., Bernardini A., Mammino A., (2000). *Determination of parameter range in rock engineering by means of random set theory.* Reliability Eng. Syst. Safety, Vol. 70, pp. 241 -261.

Trimble G., Bryman A. and Cullen J. (1986). Knowledge acquisition for expert systems in construction, *Proceedings. Symposium CIFE. Center for Integrated Facility Engrg.;* Stanford University. Stanford. Calif.

Tsai, J., Liu, A., Juan, E. & Sahay, A. (1999*). Knowledge-based software architectures: acquisition, specification and verification. IEEE Transactions on Knowledge and Data Engineering.* 11, pp. 187 – 201.

Tsonis, P., Christoulas, S. and Kolias, S. (1983). Soil improvement with coal ash in road construction; Improvement of Ground, *Proceedings of the Eighth European Conference on Soil Mechanics and Foundation Engineering*/ Helsinki/23-26 May 1983,Ed. H. G. Rathmayer and K.H.O. Saari, Vol. 2, pp. 961-964.

Van Impe, W. F., De Cock, F., Van Der Cruyssen, J. P., and Maertens, J. (1997a*). Soil improvement experiences in Belgium: Part I. Overview and dynamic compaction. Ground Improvement*, Vol. 1, pp.147 – 155.

Van Impe, W. F., De Cock, F., Van Der Cruyssen, J. P., and Maertens, J. (1997b*). Soil improvement experiences in Belgium: Part II. Vibrocompaction and Stone Columns.* Ground Improvement, Vol. 1, pp. 157 – 168.

Van Impe, W. and Madhav, M. R. (1995). Expected developments in soil improvement techniques. *Proceedings 11th African Regional Conference of Soil Mechanics and Foundation Engineering,* Cairo 1, pp. 85-142.

Vaptismas, N. & Toll, D.G. (1993). Interpreting Borehole Information. *Knowledge Based Systems for Civil and Structural Engineering.* Topping, B.H.V. (ed), Edinburgh: Civil-Comp Press, pp. 153-159.

Vedder, R. G. (1989). PC Based Experts System Shell: Some desirable and less desirable characteristics. *Expert Systems*, Vol. 1, No. 1, pp. 28-42.

Vidal, H. (1969). The principle of reinforced earth. HIGHW RES. REC, No. 282, pp.1-16.

Wahls, H. E. (1994). Tolerable Deformations. *In Proceedings of Settlement '94: Vertical and Horizontal Deformations of Foundations and Embankments*, Geotechnical Special Publication, ASCE, Vol. 2, No. 40, pp. 1611–1628.

Waterman, D. A. (1986). *A guide to Expert Systems*, Addison-Wesley Publishing Company, U.S.A. 419p

Weltman, A. J and Head, J. M. (1983). Site Investigation Manual, CIRIA Special Publication 25/PSA Civil Engineering Technical Guide 35.

Wen-Hwei, H. (1986). Rice Hulls Rice: Production and Utilization, AVI Publishing Company Inc., Westport Connection, California, USA.

West, J. M. (1976). The role of ground improvement in foundation engineering. *In Ground Treatment by Deep Compaction. The Institution of Civil Engineers,* London, pp 71-82.

Wets, G. (1998). Decision tables in knowledge-based systems: adding knowledge discovery and fuzzy concepts to the decision table formalism. PhD thesis, Leuven, Acco.

Wharry M. B. and Ashley D. B. (1986). Resolving subsurface risk in construction using an expert system. Tech. Report UTCEPM-86-1, University of Texas, Austin.

Wiig, K. M. (1994). *Knowledge management, the central management focus for intelligent-acting organization.* Arlington: Schema Press.

Wislocki, A. P. and Bentley S.P. (1989). An expert system for landslide hazard and risk assessment. *Artificial Intelligence Techniques and Applications for Civil and Structural Engineers.* Ed. B.H.V. Topping. CIVIL_COMP PRESS. pp. 249-252.

Witlox, F., (2002). MATISSE: a relational expert system for industrial site selection. *Expert Systems With Applications.* Pergamon, Vol. 24, pp. 133 – 144.

Wong, K. C., Poulos, H. G. & Thorne, C. P. (1989). Site Classification by Expert Systems, *Computers and Geotechnics,* 8, pp. 133-156.

Wong, S. V. and Hamouda A. M. S. (2000). Optimization of fuzzy rules design using genetic algorithm; *Advances in Engineering Software.* Elsevier, Vol. 31, pp. 251-262.

Yang Y. and Soh C.K. (2000). Fuzzy logic Integrated genetic programming for optimization and design. *Journal of Computing and Civil Engineering,* Vol. 4 pp. 249-254.

Yau, N.–J. and Yang, J.–B. (1998). Applying case-based reasoning technique to retaining wall selection. *Automation in Construction.* Vol. 7, pp. 271-283.

Ye, B. R.; Lu, S.Y., & Tang, Y.S. (1983). Packed sand drain-atmospheric preloading for strengthening of soft foundation. *Proceedings. 8th European Conference on Soil Mech. and Found. Engineering.,* Helsinki, pp. 717-720.

Young, W. and Hadgraft R. (1989). *Knowledge based systems in civil engineering. Civil Engineering Systems:* Decision Making and Problem Solving, Editorial, Vol. 6 Nos.1 & 2 pp 3-4.

Yu, K. and Frizzi, R. P. (1994). *Preloading organic soils to limit future settlements. In Vertical and horizontal displacements of foundations and embankments,* ASCE Geotechnical Special Publication No. 40, Vol. 1, pp 476-490.

Zadeh, L.A. (1965). Fuzzy sets: Information and Control, Vol. 8, pp.338-353.

Zadeh, L., (1976). A fuzzy-algorithmic approach to the definition of complex or imprecise concepts, Int. Jour. Man-Machine Studies 8, 249-291,

Zhang, Q., Song, J. R. and Nie, X. Y. (1991). *Application of neural network models to rock mechanics and rock engineering.* Int. Journal of Rock Mechanics and Mining Sciences and Geomechanics Abstracts, Vol. 28, No. 6, pp535-540.

Zhu, F., Li, X., Wang, S., and Li, G. (2000). *Expert System application to the selection and design of retaining structures.* Dongbei Daxue Xuebao/ Journal of Northeastern University, Ei Compendex, Vol. 21, Issue 3, pp 298-300.

Zhu, J, -H., Zaman, M. M., and Anderson, S.A. (1998). *Modeling of shear behaviour of a residual soil with Recurrent Neural Network.* Int. Journ. Numerical and Analytical Methods in Geomechanics, John-Willey & Sons, Vol. 22, No. 8, pp 671-687.

Zhu, J, -H., Zaman, M. M., and Trafalis T. B. (1996). *Prediction of shear stress-strain behaviour of soil with recurrent neural network,* In: Proc. 1996 Artificial Neural Networks in Engineering. ASME, pp 809-814